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Holocene sedimentation, stratigraphy, biostratigraphy, and history of the Canning Coast, north-western Australia

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Abstract

Holocene environments along the Canning Coast are of four types: (1) rocky shores of Mesozoic to Tertiary rock and semi-indurated desert sand dunes; (2) rocky shores of Quaternary limestone; (3) sand-dominated flats and beaches/dunes along open coasts; and (4) protected mud-dominated embayments, lagoons and bays. Sediments vary markedly in origin, grainsize (boulders to mud), and composition (quartz sand, shells and their fragments, foraminifera, ooids, beachrock intraclasts, lithoclasts, and carbonate mud). Twelve new Holocene stratigraphic units are described from this region: Shoonta Hill Sand, Eighty Mile Beach Coquina, Cable Beach Sand, Port Smith Sand, Race Course Plains Coquina, Sandfire Calcilutite, Cape Gourdon Formation, Barn Hill Formation, Church Hill Sand, Horsewater Soak Calcarenite, Kennedys Cottage Limestone and Willie Creek Calcarenite. The current depositional nature of most of these units indicates their recent age, but radiocarbon dates confirm the Holocene age for all units, with the oldest date being 7450 ^{14}C yrs BP and the youngest 900 ^{14}C yrs BP. The three limestones (Willie Creek Calcarenite, Kennedys Cottage Limestone, and Horsewater Soak Calcarenite) and inland occurrences of Sandfire Calcilutite are the oldest Holocene formations in the region. For the contemporary units, the Port Smith Sand generally underlies all unconsolidated Holocene formations. The Sandfire Calcilutite, Cable Beach Sand, and Eighty Mile Beach Coquina are laterally equivalent representing a change from low energy progradational to high energy progradational to high energy dominantly erosional. Shoonta Hill Sand caps those sequences formed under high energy conditions, but also overlies Sandfire Calcilutite where retrograding. The Barn Hill Formation, Church Hill Sand, and Cape Gourdon Formation are developed where coastal erosion cuts into Pleistocene dunes, mixing it with carbonate grains; here, coastal sedimentation involves interactive accretion of beaches, dunes and alluvial fans. Mangroves and fossil molluscs (involving various types of biocoenoses and thanatocoenoses) were used to biostratigraphically characterise the formations, determine depositional environments, and assess the extent of coastal reworking. The mollusc fauna signal that there have been changes in substrates, and the regional stratigraphy points to alternating erosion and deposition and to major substrate changes in tidal zones. This is reflected in the thanatocoenoses on beaches and within polymictic shell gravels of the Eighty Mile Beach Coquina. Radiocarbon dating of stratigraphic interfaces and tide level markers shows MSL was + 2 m between 7500 and *circa* 5000 yrs BP, + 1.5 m between 4500 and 2500 yrs BP, and at its present position by 2100 yrs BP. The post-glacial marine transgression flooding into the western margin of the Great Sandy Desert 7500 yrs BP created a complex jagged and locally rocky coastline with numerous embayments that has since been smoothed out. Three types of shore were developed initially: large funnel-shaped embayments, small embayments, and rocks and desert dunes exposed at the coast. With a + 2 m sea level, waves entered small embayments more pervasively, and many embayments were sand-dominated, but with accretion of barriers (later to be lithified), and concomitant fall of sea level, there was more effective protection of embayments, and carbonate mud began accumulating in their interiors. For deeply indented coasts, accumulation of mud had been prevailing, but with a falling sea level, the coast prograded and the seafront became more wave exposed, resulting in alternating coastal advance and retreat, forming mud ribbons, barriers, cheniers, and shell concentrates.

Keywords: Canning Coast, Canning Basin, Holocene sedimentation, Holocene stratigraphy, Holocene biostratigraphy, sea-level history, Holocene palaeogeography

Introduction

The Canning Coast in north-western Australia, fronting, to a large extent, the western margin of the Great Sandy Desert, and comprising the Quaternary coastal fringe of the Canning Basin (Semeniuk 1993a; and Figure 1), presents a complex of sedimentary environments and facies that are the result of autochthonous to allochthonous carbonate sand sedimentation, allochthonous carbonate mud sedimentation, and allochthonous reworking of quartz-dominated desert dunes. As a coastal sector, one of its characteristic features is the negligible fluvial input from the hinterland. As such, coastal sedimentation, where dominated by mud, is composed of carbonate mud. Sedimentologically and compositionally it is a mixed carbonate and siliciclastic complex. The entire Canning Coast also has been subject to a variable sea-level history that has resulted in changes in coastal configuration and hence in sedimentation style. As a consequence, a variety of Holocene stratigraphic units occur along this coastal zone, reflecting variation in sedimentary patterns, accretionary and erosional coastal history, and relative sea level changes. These stratigraphic units have accumulated, and are accumulating, in various shore environments that are generating distinct sedimentary bodies which, to date, have not been formally described or defined.

Sedimentary environments along the Canning Coast occur in a macrotidal setting which varies in tidal range from 6 m in the south to 10.5 m in the north (Calder 1979; Anon 1991). Hence the individual, distinct, tidally-related lithosomes are of reasonable consistent lithology and thickness to be clearly and readily recognisable regionally. Since most occur along the entire *circa* 600 km length of the coastal zone of the Canning Basin they can be justifiably assigned formational status. In addition to their distinct lithology, the stratigraphic units have been and currently are related to tidal levels. As such, these stratigraphic units also are useful as regional palaeo-environmental indicators, and the identification of these Holocene Formations, and their assignment to standard coastal sequences, helps unravel the sedimentologic patterns and Holocene coastal history in this part of Western Australia, and helps reconstruct Holocene coastal palaeogeography along the Canning Coast.

The objectives of this paper are manifold. They are: to provide a Quaternary stratigraphic framework for the Canning Coast region; describe the coastal settings host to the Holocene stratigraphic sequences; describe the modern sedimentary environments wherein the various Holocene lithotopes occur and the lithosomes have been generated; describe and formally define the Holocene stratigraphic units in their type formative coastal locations; identify and describe the coastal biocoenoses and thanatocoenoses in the region to characterise the stratigraphic units by their fossil assemblages; provide radiocarbon ages of the Holocene units, relate the Holocene units to MSL; describe the Holocene sea-level history of the region; and interpret the origin of the Holocene stratigraphic units along the Canning Coast. Such information assists in understanding the evolution of Holocene sedimentation in the region and the control that Pleistocene and earlier Holocene sedimentation patterns exerted on coastal geomorphology and modern sedimentation. It also assists in reconstructing the palaeogeography of the Canning Coast during the Holocene. In a larger multidisciplinary perspective, the information presented in this paper can form the foundation to coastal hydrogeology useful to the study of coastal ecology, the framework for studying mangroves in relation to their habitats, a framework to understanding Holocene middens, and a basis for coastal conservation in geoheritage.

There are also a number of Pleistocene stratigraphic units along the Canning Coast equivalent to the Holocene units to be described in this paper; these include limestone lenses in red/orange sand, indurated (marine) calcilutite, aeolianite, and calcreted shelly calcarenite. The focus in this paper, however, is on the Holocene stratigraphic units. The Pleistocene stratigraphic units will be the subject of a later report.

Geographic names mentioned throughout the text are shown in Figure 2.

Materials and methods

Regional traverses and transects were undertaken to determine types and distribution of stratigraphic units. The location of these traverses and transects are shown in Figure 3A. Stratigraphic data for this paper derive from four types of field situations: 1. natural cliff exposures of dunes, limestones, and some muddy sequences; 2. natural tidal creek bank exposures of muddy sequences; 3. coring and augering at many sites; and 4. trenches. Locations of study sites such as cliffs, and auger or drill sites are shown in the various stratigraphic profiles presented later.

Sediments and rocks are described in the field sequentially from large scale to small-scale in terms of geometry of stratigraphic units, structures, fabric of sediments, texture, and composition. Samples in the laboratory were examined under binocular microscope, and the carbonate nature of whole samples (e.g., muds), and the carbonate nature of individual grains were determined by reaction with drops of HCl under the stereoscopic microscope. Some 100 selected samples of limestone and sand were prepared as thin sections and examined under a petrographic microscope. Selected mud samples were examined under a Scanning Electron Microscope (SEM) at the CSIRO laboratories, Kensington. Samples of mud were also separated into size fractions of < 4 μm, 4–20 μm, 20–40 μm, and 40–60 μm for X-ray diffraction analyses to determine mud-sized mineralogy. Some of these XRD results are reported here, but the details will be presented in a later study.

Some twenty nine samples of shell, carbonate mud, or mangrove wood, collected at various stratigraphic and geographic locations along the Canning Coast, were submitted for radiocarbon analyses in this study. The geographic locations of the samples are shown in Figure 3B. Shell was collected from various stratigraphic units: mangrove environment shelly fauna, low tidal flat shelly fauna, chenier shell deposits, and beach shell. These shells were sieved from the sediment, washed clean of adhering sediment, and separated into species for processing at the CSIRO laboratories in Adelaide, or Krueger Geochron Laboratories (USA). Where

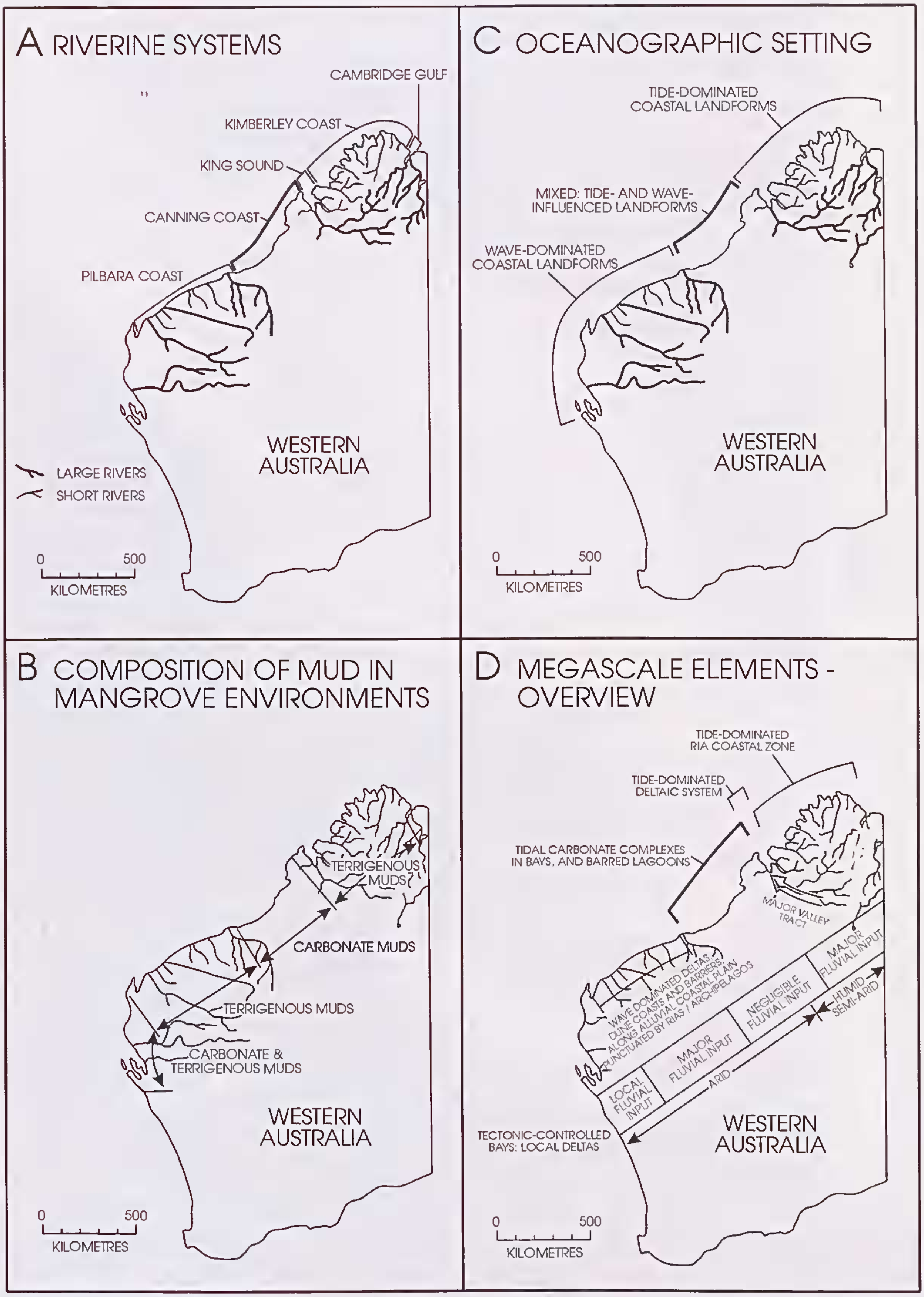


Figure 1. Regional setting of the Canning Coast (from Semeniuk 1993a). A. Canning Coast as a system that receives little or no fluvial input compared to the neighbouring sectors. B. Carbonate mud dominates the Canning Coast in contrast to neighbouring sectors. C. Oceanographic setting of the Canning Coast which is mixed tide and wave influenced. D. Summary of megascale coastal features and sediment composition that sets the Canning Coast apart from its neighbouring sectors.

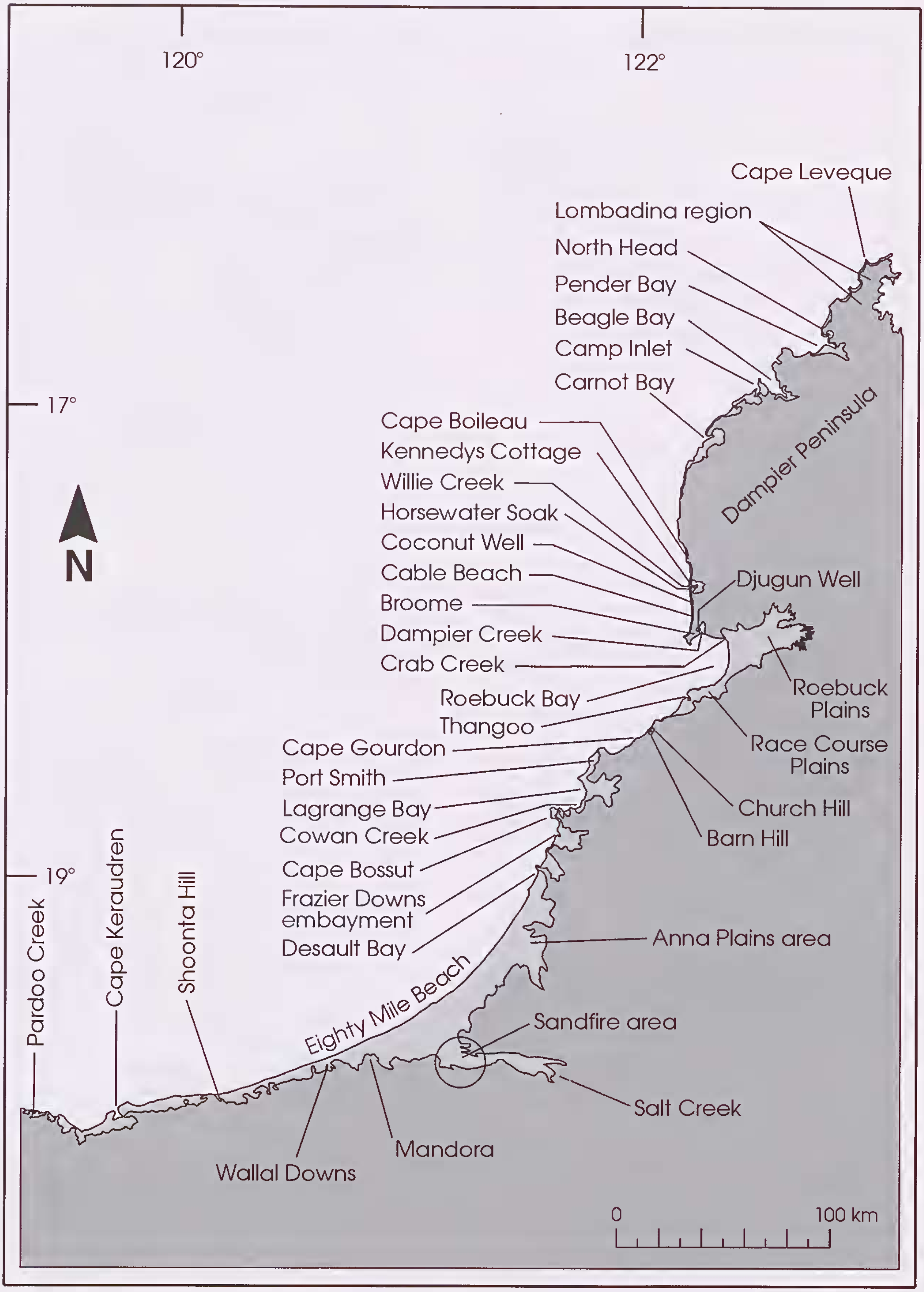


Figure 2. Geographic locations mentioned in text.

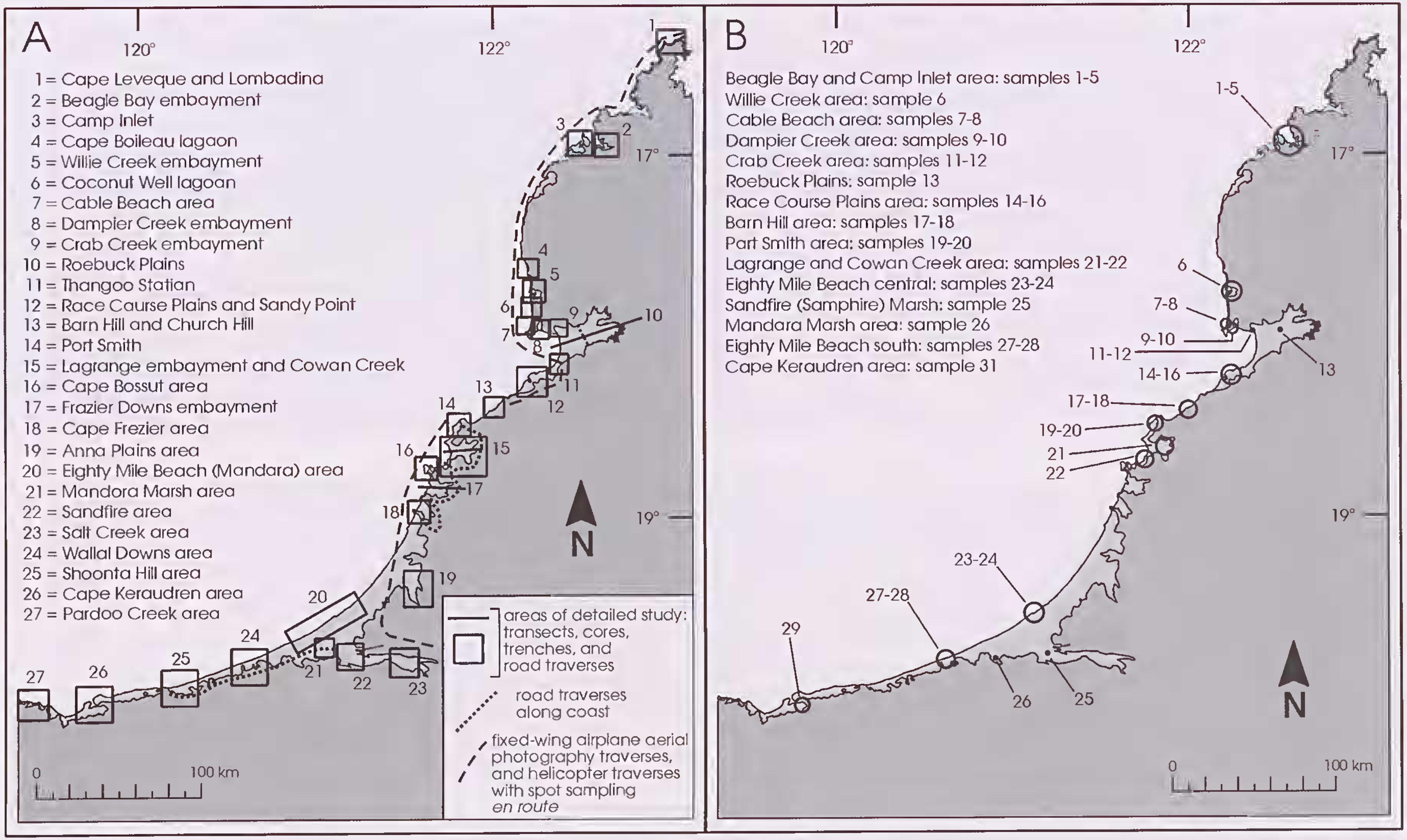


Figure 3. Location of study sites and sampling sites. A. Location of detailed sampling sites where traverses, stratigraphic profiles and geomorphic mapping were undertaken, and the routes for road traverses, helicopter traverses and fixed-wing airplane oblique aerial photography. B. Sites for samples for radiometric analyses.

insufficient individual shells of a given species were present at a stratigraphic level for analysis, mixtures of whole shells were provided to the laboratory. At one site, where shells were absent in a calcarenite, a whole-of-sample was provided for analysis to determine radiocarbon age from the carbonate grain content. Carbonate mud for radiocarbon determination was sieved to remove any sand and gravel fractions, and then dried. Mangrove wood was dried prior to analysis. Details of material used in the analyses in terms of field codes, laboratory codes, their stratigraphic occurrence, and rationale for sampling are presented with the radiometric results later in the paper.

Mollusc shells are important components of the sediments and sedimentary rocks of the Holocene sequences along the Canning Coast. Often they biostratigraphically characterise the Holocene Formations, and also provide insights into depositional processes. For typifying the Holocene Formations in terms of their molluscan biota, and for assessing whether the assemblages were biocoenoses or thanatocoenoses, shells were randomly collected in bulk in their hundreds from key sedimentary lithotopes, or sieved from bulk-collected sand, or opportunistically where available from lithified stratigraphic units. This was a bias in determining diversity of the fossil mollusc fauna that developed in collecting methods in that proportionally fewer shells could be collected from lithified Formations (that present themselves only as cliffs) compared to those that could be collected from sedimentary surfaces and from sediment that could be sieved. The collections throughout the Holocene Formations were extensive, but not species-exhaustive, in that the objective was to characterise the assemblages, not determine the full extent of the biodiversity in the region or biodiversity within a lithosome. Emphasis was placed on collecting dead shells that are preserved in modern lithotopes, and those fossils embedded in the limestones, and so the species lists provided in this paper should not be used to ascertain the biodiversity of the extant molluscan biota. In the laboratory, the shells were sorted to species level and counted, providing a measure of the proportion of species that comprised the mollusc fossil and subfossil assemblages. The most abundant five (or ten) species of molluscs from a stratigraphic unit were selected for the illustrations (to be presented later in this paper) to biostratigraphically characterise a Formation. Source references used for identifying molluscs are Wilson & Gillett (1974), Coleman (1975), Lindner (1977), Eisenberg (1981), Slack-Smith (1990), Lamprell & Whitehead (1992), Wilson (1993a, 1993b), Beesley *et al* (1998), Johnson & Black (1998), Lamprell & Healy (1998), Norman & Reid (2000), Abbott & Dance (2000), Wells & Bryce (2000), and Jones (2004).

Terms and definitions

General terms

Abbreviations of tidal levels used in this paper are as follows: LAT = lowest astronomical tide, MLWS = mean low water spring tide, MLWN = mean low water neap tide, MSL = mean sea level, MHWN = mean low water neap tide, MHWS = mean high water spring tide, and HAT = highest astronomical tide. Since many of the study sites in this paper are located in remote regions, distant from bench marks and standard ports, three techniques were used to determine the height of stratigraphic units relative to the Australian Height Datum (AHD) and to compare modern and ancient tidal-level diagnostic facies: (1) the water mark of the highest tide delineated by high tide deposits was used as the level of HAT, using Broome as the standard port for tidal levels in northern areas, Port Hedland in southern areas, and calculated range and heights for intermediate areas; (2) the position of the water level for a given time was used in conjunction with the predicted tide and the standard tidal curve, again using the tide curve of Broome as the standard port in northern areas, Port Hedland in southern areas, and calculated range and heights for intermediate areas; and (3) using the base and/or top of modern tidal-level diagnostic facies and comparing them to the equivalent facies for earlier Holocene units.

A lithosome is rock mass or sediment mass of essentially uniform or uniformly heterogeneous lithologic character, having intertonguing relationships or sharp contact in all directions with adjacent masses of different lithologic character (modified after Bates & Jackson 1987). A lithotope is an area or surface of uniform sediment, sedimentation, or sedimentary environment, including associated organisms (Bates & Jackson 1987). The term fossil is used in this paper in the traditional sense for the biota that is embedded in sedimentary rock (*e.g.*, limestone), or embedded at some depth (> 20 cm) in mud, sand, or gravel. Many shells and other skeletal biota, however, are surface and near-surface accumulations of recently living fauna, and the term subfossil refers to this material which occurs on the surface as empty shells, or at shallow depth (< 20 cm). The term coquina is used in this paper to refer to shell gravel. While generally the term has been used in the literature to refer to shell gravel, usually there is no differentiation as to the degree of heterogeneity of this gravel. For descriptive, and interpretive purposes, three types of coquina are recognised in this study: monomictic coquinas (or monomictic shell gravel), composed dominantly of one species of shell, oligomictic coquinas (or oligomictic shell gravel), composed of several species of shell, and polymictic coquinas (or polymictic shell gravel), composed of a wide variety of shell species; the concept and terms derive from sedimentary petrology wherein sedimentary rocks are said to monomictic, or polymictic if they are composed of one, or more than one mineral species, respectively. Root-structured refers to that sediment structure wherein roots of mangroves and samphires have left a discernable vertically penetrating and ramifying pattern, often still with plant material or organic matter within. Burrow-structured refers to that sediment, soil, or sedimentary rock structure wherein there is an array of vertical to oblique burrows and filled burrows. Bioturbated is the term used to describe structures generated by fauna and plants where the root-structuring and burrow-structuring have become dense enough to produce swirls and mottles of overlapping biogenic structures in a sediment, soil or limestone. Beach rock is the indurated sand at the beach face, formed by interstitial precipitation of aragonite or Mg-calcite; though indurated, it preserves the layering, embedded shells, and bubble structures of the sediment. Bubble sand is the vesicular structure formed in the upper tidal zone of a beach or tidal sand body. Intraclasts are intraformational clasts (after Folk 1962) where there is cementation, erosion or reworking, and clast formation within a given current sedimentation cycle. Lithoclasts are extra-formational clasts, that are rock fragments derived from older Formations. In this study, intraclasts mostly are modern carbonate-cemented sediments that have been reworked as clasts into the current sedimentary cycle; typically they are fragments of beachrock. Lithoclasts mostly are fragments of rock eroded from Mesozoic sandstone, or ferruginised sandstone, ironstone, or Pleistocene limestones.

Biocoenoses and thanatocoenoses of mollusc assemblages and mangroves

Mollusc shells and mangrove vegetation as fossils and subfossils were used in this study in a number of ways: to characterise some of the Holocene Formations (as listed in the descriptions of the new stratigraphic units); to determine the environment of deposition of some of the older Formations and; to assess the extent of reworking and mixing that has taken place along the coast. Being gravel-sized, mollusc shells specifically provide a different measure of the extent of sedimentary reworking and transport compared to sand grains because they are less readily transportable and because many of the species are environment-indicative and therefore can clearly show an exogenic provenance. For this reason, some discussion of types of fossil assemblages (*i.e.*, biocoenoses and thanatocoenoses) is provided as background to interpreting these assemblages along the Canning Coast.

A biocoenose (or biocoenosis) is a life assemblage of organisms, while a thanatoceonose (or thanatocoenosis) is a death assemblage (Raup & Stanley 1971; Bates & Jackson 1987). Bates & Jackson (1987) provide these definitions: a bioceonosis is "a set of fossil remains found in the same place where the organisms lived"; a thanatocoenosis is "a set of fossils brought together after death by sedimentary processes, rather than by virtue of having originally lived there collectively", or "a group of fossils that may represent the biocoenosis of an area plus the thanatocoenosis of another environment". Over the years, there has been confusion and misapplication of these terms, because their use has been applied from two different disciplines, *viz*, that of ecology and that of palaeoecology. For instance, while ecologists emphasise that a biocoenosis is to be applied to living assemblages, palaeoecologists view biocoenosis as the group of organisms that once lived together and are now associated together in death.

True biocoenoses, when they were extant, would have been composed of organisms that could be preserved (*e.g.*, the skeletal organisms such as molluscs) as well as a plethora of those that had little chance of preservation (*e.g.*, macrophytes, polychaetes, most crustaceans). Generally the preservation of the full complement of life assemblages is not possible. Hence, the concept of biocoenosis as a life assemblage in the palaeontological record at best is an approximation, with a focus only on organisms that have been preserved. In this matter, I agree with Imbrie & Newell (1964), that all fossil assemblages strictly are thanatocoenoses, and with Ager (1963) that no fossil assemblage is a biocoenose in the way the term is understood by ecologists. However, the intention in palaeontology and palaeoecology of separating biocoenoses from thanatocoenoses is to distinguish fossil assemblages that had accumulated nearly *in situ*, or autochthonously (and hence approximate former palaeoecological situations) from those that are definitely haphazard, or random, or fortuitous aggregations, or of various ages, brought together by any number of processes, that hence bear little relationship to the original palaeoecological assemblage and consequently cannot be used in palaeoecological reconstructions. It is worthwhile to have terms that attempt to distinguish between the products of these situations, and rather than coin new terms to encapsulate these concepts, the existing terms are employed but with strict definition as to their usage in this paper.

In this context, the terms biocoenosis and thanatocoenosis are used in this paper *in a palaeontological sense* to characterise the Holocene fossil and subfossil components in the region. With the use of descriptors, the terms are helpful in the interpretation and reconstruction of biotic assemblages in the stratigraphic sequences along the Canning Coast.

However, while the terms are conceptually useful, there have been difficulties in the literature with their precise definitions, reflecting the ecological *versus* palaeoecological experience (and bias) of authors. For instance, there are various ideas as to what constitutes a biocoenosis and a thanatocoenosis depending on the degree that fossils are viewed to reflect the palaeoecological situation, and the degree that transport is involved in aggregating the fossils, and in this context, there has been some debate in the literature. For instance, some authors consider that even if a fossil record was monospecific, and accumulated after death to form a monospecific layer, that the deposit is still a thanatocoenosis (Štradner 1987). Martin & Henderson (2003) highlight in a modern environment how a storm-generated inland molluscan assemblage (and definitely a thanatocoenosis) in time through synsedimentary diagenesis eventually simulates a biocoenosis and voicing a caution in the interpretation of biocoenoses and a thanatocoenoses. In Holocene environments, if the assemblages are considered to be autochthonous, time averaging, to some extent, can circumvent the problems of comparing and interpreting a biocoenosis with thanatocoenoses, created by annually or inter-annually varying biocoenoses (Fursich & Aberhan 1990), in that such an approach will define a fossil assemblage that reflects long term ecological responses and assemblage composition. In this context, clearly, many palaeoecological reconstructions are dealing with time averaged assemblages and therefore have some degree of validity.

To some extent, the matter of scale has to be incorporated into the concept of biocoenosis and thanatocoenosis. There may be more representation of biocoenosis or thanatocoenosis at the smaller scale in some environments (*e.g.*, shipworm *in situ* in a mangrove trunk, while the mangrove trunk itself has been exported from its lithotope), and more faithful representation of biocoenosis at the larger scale in others (where the boundary of a lithotope is involved, for instance, in defining the boundary of a palaeoecological unit).

Application of the terms can be further complicated where there is a range of fossil and subfossil assemblages that cannot be assigned simply to either biocoenosis or thanatocoenosis, in that they manifest gradation between these two extremes. This latter situation, for instance, is especially important in this study of the Canning Coast. It is worthwhile, therefore, to explore the connotations of the terms biocoenosis and thanatocoenosis and refine their meaning for use in this paper.

The best example of an assemblage that can form a biocoenosis is an *in situ* encrusting assemblage, such as a coral reef. In a coral reef, the skeletal fauna, encompassing corals, bryozoans, embedded molluscs, and lithophagic molluscs are preserved wholly *in situ*, though the non-skeletal forms have little chance of preservation (as noted above). The assemblage may preserve the proportion of skeletal macrofauna that were living at the time of accretion. This is an ideal, relatively unambiguous "life assemblage", and if preserved in the fossil record can be described as a "biocoenosis". In this situation, the biotope is also the lithotope (sedimentary setting). In contrast, in the coral reef context, sandy and gravelly lagoons accumulating detritus from the reef through wave and storm reworking commonly are underlain by fossil and subfossil assemblages that can be described as thanatocoenoses.

Accumulations of shells under seagrass cover on a seagrass bank, as described by Davies (1970) in Shark Bay, and Semeniuk (1997) Rottnest Shelf Coast, provide a second example of a type of biocoenosis, but while the shells live and die on and in the sediment in this environment, and some organisms living on the seagrass blades fall to the sea floor after their death, or the death of the seagrass itself (T A Semeniuk 2000, 2001), there is some degree of disruption after death by burrowing organisms, by scavengers, and perhaps some limited wave reworking (but not transportation from the biotope or lithotope). Shells and other skeletal fauna in the sediment may be *in situ* and still articulated, or disaggregated and locally scattered by bioturbation (Hagan & Logan 1974). In the final time-averaged shelly accumulation, the internal composition and diversity of the dead shell deposit may reflect, more or less, the internal composition and diversity of the living skeletal components of the assemblage. The lithotope occupies the same space as the biotope. Again, to some authors, as it reflects the living assemblage in composition, this is still a biocoenosis; to others it is a thanatocoenosis, representing accumulation, after death, of the components of the assemblage.

Mangrove environments provide another example of a biocoenosis (see Figure 5 in Semeniuk 1981a). There may be *in situ* tree trunks, toppled tree trunks and fallen tree branches, wood fragments, *in situ* molluscs (Teredinidae) that have bored into the tree trunks, and encrusting organisms on the tree trunks such as oysters and barnacles (that commonly have fallen to the substrate surface, or that through fish foraging and crab predation have been broken and have fallen to the substrate surface). There also may be preservation of vagile gastropods comprising various species of the Potamididae; and there are a variety of Littorinid and Neritid gastropods that are mobile on the trees and on the substrate; in-faunally, there are bivalves and many species of crustacea. Given that there is bioturbation and biogenic shell fragmentation, and widespread decay of plant material, and given that the generally sheltered nature of a mangrove environment (with its fine-grained sediment) has little chance of wave and current reworking, what is preserved in a mangrove environment lithotope generally reflects locally generated fossils and subfossils. Essentially, the lithotope occupies the same space as the biotope. To some authors, particularly palaeoecologists, this is a biocoenosis (as it mirrors the living assemblage in composition); to others it is a thanatocoenosis, representing accumulation after death of the components of the assemblage.

Beach environments provide another contrast to these concepts, taking the notions of biocoenosis and thanatocoenoses to their limit. If the beach is inhabited by a monospecific shell assemblage, say, *Donax faba*, there may be accumulation of this shell that has been disarticulated, perhaps fragmented, transported, reworked, and accumulated as shell gravel, and strictly, though not *in situ*, the shell content *does represent the composition of the living assemblage*. The biotope occupies the same space as the lithotope, even though there has been pronounced disarticulation, transport and deposition, reworking and re-deposition within the lithotope. Again, such assemblages are considered by some authors as biocoenoses, and by others as thanatocoenoses. On the other hand, an accumulation of shells of *Donax faba* transported to another lithotope would be considered by nearly all authors to be a thanatocoenosis even though the shell assemblage is the same as the living assemblage (*i.e.*, 100% *Donax faba*). The accumulation of mixed shells transported from a variety of habitats and deposited into the one lithotope by say, a storm, also is a thanatocoenosis.

In this paper, the extent that biotope composition mirrors, or is co-incident with lithotope distinguishes bioceonoses from thanatocoenoses in the first instance, and distinguishes different types of bioceonoses. That is, biocoenosis or thanatocoenosis refers to the composition of the shell assemblages and how closely it represents the original living assemblage, and for molluscs, the terms refer to whether the fossil or subfossil assemblage *more or less reflects the composition of the original mollusc assemblage*. The descriptor terms "autochthonous" and "allochthonous" are then used to refer to the extent that the shells have been transported (from their lithotope of habitation into a different lithotope).

The various terms used to describe these situations are as follows:

1. *in situ* biocoenosis
2. autochthonous biocoenosis
3. allochthonous biocoenosis
4. allochthonous partial biocoenosis
5. mixed biocoenosis/thanatocoenosis
6. allochthonous thanatocoenoses

Table 1

Definition of mollusc assemblage types

Assemblage type	Definition and examples from the Canning Coast
in situ biocoenosis	*in situ* accumulations of encrusting organisms are *in situ* biocoenoses (they are clearly also autochthonous) or where articulated shells and ichnological forms are *in situ*
autochthonous biocoenosis	accumulations of shells within the environment of habitation, but not transported out of the habitat, are referred to as biocoenoses in this study, as they compositionally reflect the life assemblage; they are specifically referred to as autochthonous biocoenoses – the term "autochthonous" referring to lithotope setting, the term "biocoenosis" referring to the biotope setting; shells that have been disaggregated (disarticulated), very locally mobilised, and still in their environment of habitation are autochthonous, but no longer strictly *in situ* (for instance as articulated shells)
allochthonous biocoenosis	accumulations of habitat-specific shells that have been transported out of their habitat are allochthonous biocoenoses
allochthonous partial biocoenosis	oligomictic accumulations of habitat-specific shells that have been selectively transported out of their habitat are allochthonous partial biocoenoses; the descriptor "partial" refers to the fact that only portion of the original biocoensis has been transported; there are no other, or negligible contributions from other assemblages
mixed biocoenosis/ thanatocoenosis	a major part of the assemblage is a biocoenosis, but some exogenic shells have been transported to the lithotope; the entire assemblage thus carries two signatures
allochthonous thanatocoenosis	accumulations of mixed shells, reworked and transported from various habitats are allochthonous thanatocoenoses

Definitions of these terms with examples are provided in Table 1.

This method of classifying fossil and subfossil assemblages differs from that presented by Craig & Hallam (1963), in that it represents a greater range of possible preservation types. Craig & Hallam (1963) identify buried *in situ* life assemblages (= *in situ* autochthonous biocoenosis), and three types of death assemblages (defined to be fossils that are transported), *viz.*, indigenous, wherein the fossils are in the same environment as the living community (= autochthonous biocoenosis), exotic, wherein the fossils are derived from different but contemporaneous environment (= allochthonous thanatocoenosis), and remanié where the shells are derived from older rocks. In their classification, Craig & Hallam (1963) do not recognise categories of allochthonous biocoenosis, allochthonous partial biocoenosis, or mixed biocoenosis/thanatocoenosis.

Some of the assemblage types outlined in Table 1 are encompassed by the chart of the possible fate of fossils presented by Ager (1963). However, Ager (1963) does not provide terms for the various categories.

Regional setting

The coastal zone of the Canning Basin is termed the Canning Coast (Semeniuk 1993a, and Figure 1). Located in an arid to semi-arid climate (Gentilli 1972), it is situated between Pardoo Creek and Cape Leveque, and is bordered to the southwest by the Pilbara Coast (Semeniuk 1996) and to the northwest by King Sound (Semeniuk 1980). The boundaries of the Canning Coast (regionally) are sharp: Pardoo Creek, a northern distributary of the DeGrey River Delta demarcates its junction with the Pilbara Coast (a delta-dominated sector, and hence a terrigenous-dominated sedimentary system), and Cape Leveque demarcates its junction with the estuarine gulf of King Sound (another terrigenous sedimentary system).

The Canning Coast comprises stretches of open beaches and barrier dunes, Quaternary limestone ridge barriers, local rocky shores cut into bedrock of Mesozoic age, tidal embayments, lagoons and bays (Semeniuk 1993a). Unlike its adjoining sectors of terrigenous-dominated sediment to the southwest and northwest, respectively, sedimentologically, the distinguishing feature of the Canning Coast is that its fine-grained tidal deposits are dominated by carbonate mud (Figure 1).

In terms of climate, the Canning Coast is tropical arid in southern sectors, and tropical semi-arid in northern sectors. The Port Hedland region, bordering the southwestern end of the Canning Coast, has a tropical arid climate with a winter dry season and a summer wet season (Bureau of Meteorology 1973, 1975, 1988); its mean annual rainfall is 313 mm; the average monthly temperatures range from 25°C to 36°C in January to 12°C to 27°C in July. Its annual evaporation is *circa* 3400 mm. The Broome region has a tropical semi-arid monsoon climate also with a winter dry season and a summer wet season (Bureau of Meteorology 1973, 1975), with a mean annual rainfall of *circa* 600 mm; average monthly temperatures range from 26°C to 33°C in January to 13°C to 29°C in July. Its annual evaporation is *circa* 2800 mm. Summer is the period of cyclones (Lourensz 1981), and these periodically impinge on the coast bringing wind with speeds that may exceed 160 kph, delivering some 40–50% of the summer rainfall (Bureau of Meteorology 1973, 1975; Lourensz 1981), and generating storm surges.

Various physical coastal processes, *viz.*, waves, tides, wind, and storms, have combined to influence the development of geomorphic setting and the development of Holocene stratigraphic units along the Canning Coast. Oceanographically, the shore zone is a mixed tide- and wave-influenced system (Figure 1) where, although the tidal regime is macrotidal, wave processes are still effective in developing coastal landforms. Anthony & Orford (2002) similarly place this coastal region into a category of wave- and tide-dominated coast. Tides are semi-diurnal, increasing in amplitude from south to north (Calder 1979; Anon 1992): mean spring tidal range is *circa* 6 m in the south of the Canning Coast near Port Hedland, and *circa* 8 m to the north in the Broome region. At Broome, the maximum spring range during equinoctial tides is 10.5 m, and the mean spring range is 8.2 m. Wright *et al.* (1982) carried out field investigation of hydrodynamic processes, processes of sediment entrainment and suspension, and morphologic change along Cable Beach in part to characterise the oceanographic setting of this macrotidal beach. They found waves had heights of 0.5 to 1.2 metres and periods of 9 to 13 seconds.

The development of coastal forms, such as dunes, and barriers emanating from headlands, and the development of sediment types and stratigraphic sequences, are also influenced by onshore winds. Morning winds in January derive from many sectors in the Port Hedland area and dominantly from westerly sectors in the Broome area (Bureau of Meteorology 1988). Afternoon winds in January derive from northwest and, to a lesser extent, northern sectors in the Port Hedland area in January, and dominantly from western and, to a lesser extent, from north-western sectors in the Broome area, often in the range of 10–30 km/hr in both regions. Morning winds in July derive from dominantly eastern and south-eastern sectors in both the Port Hedland and Broome regions. Afternoon winds in July derive from a variety of sectors in the Port Hedland region but northerly, easterly, south-easterly and north-westerly are dominant; afternoon winds in the Broome region derive from west, southwest, south, and south-eastern sectors; again, winds are often in the range of 10–30 km/hr in both regions. As a result, there is a strong component of longshore drift to transport sediments, and on-shore winds to develop local wind waves.

As is typical of much of the open coast of Western Australia, the wave climate of the Canning Coast is swell and wind waves. In this region, swell derives from the Indian Ocean and from that refracted from south-westerly directions, hence, westerly swell is dominant. Wind waves are driven by the local wind systems, and hence they change seasonally. Swell and wind waves propel sediment transport causing longshore drift.

The stratigraphic framework for the coastal types

The Canning Coast is underpinned by a variety of pre-Holocene stratigraphic units and earlier Quaternary units, that determine coastal form, and that have influenced Holocene coastal sedimentation. Not all of the

Table 2

Formations that occur in the Canning Coast region that influence coastal form

Formation	Lithology	Occurrence and influence on coast
Quaternary		
Christine Point Clay	grey kaolinitic clay with *in situ* mangrove stumps	in the Beagle Bay and Camp Inlet areas, but no significant influence on coastal form
North Head Limestone	bioclastic and quartzose fine calcarenite	forms the western cliffs near Pender Bay in the northern part of the Dampier Peninsula
Chimney Rock Oolite	calcreted, well cemented oolitic limestone	forms the western cliffs near Pender Bay in the northern part of the Dampier Peninsula
Mowanjum Sand	structureless red sand (red sand and red muddy sand, root structured and mottled)	occurs discontinuously along the entire Canning Coast; forms local cliffs, and is the source for much of the coastal sand through wave and aeolian reworking; this unit dominates the pre-Holocene Canning Coast
Tertiary		
Borda Sandstone	fine sandstone	along the western cliffs in the northern part of the Dampier Peninsula, but no significant influence on coastal form
Mesozoic		
Emeriau Sandstone	cross-bedded, poorly sorted sandstone, and minor conglomerate	only locally forms cliffs, but no significant influence on coastal form
Frezier Sandstone	poorly bedded, fine to coarse, poorly sorted sandstone and minor conglomerate of early Cretaceous age	forms scattered cliffs and headlands, or has been the foundation of headlands in the Desault Bay to Cape Gourdon area
Parda Formation	siltstones and minor fine-grained sandstone of early Cretaceous age	forms cliffs and headlands in the Cape Gourdon area
Melligo Sandstone	laminated to thin bedded, fine to medium sandstone of early Cretaceous age	forms cliffs and headlands in the Cape Gourdon area
Broome Sandstone	cross-bedded, bedded to laminated, fine to very coarse sandstone, mudstone and minor conglomerate of early Cretaceous age	forms prominent cliffs and headlands in the Cape Gourdon area and the western cliffs in the southern part of the Dampier Peninsula

stratigraphic units have been formally named. In addition, there is an occurrence of a Holocene mangrove-bearing clay unit that is referred to the Christine Point Clay.

The main formally named stratigraphic units defined and/or mapped by other authors along or within the region of the Canning Coast, as well as extrapolated from the shores of the King Sound area, are presented in Table 2. The information has been drawn from Traves *et al.* (1956), Brunnschweiler (1957), Johnstone (1961), Lindner & McWhae (1961), Veevers & Wells (1961), Hickman & Gibson (1982), Towner (1982), Gibson (1983a, 1983b, 1983c), Hickman (1983), Towner & Gibson (1983) and Hocking *et al.* (1987).

Additionally, there is a range of un-named units of Tertiary and Quaternary age which also have influence on coastal form and coastal sedimentation; these are described below in terms of lithology, occurrence and influence on the coast.

1. ferruginised sandstone; a black to dark grey iron-oxide-impregnated coarse and very coarse angular quartz sandstone; it generally is more common in the southern to central parts of the Canning Coast;
2. ironstone gravel and breccia; a gravel to cobble to boulder deposit of ironstone clasts and ferruginised sandstone, eroded from the ironstone duricrusts of the hinterland; it generally is more common in the central to northern parts of the Canning Coast; a sheet of ironstone gravel also forms a horizon between the Pleistocene Mowanjum Sand and the Holocene units; and
3. mottled muddy sand, mud and gravel; a yellow to brown to cream sedimentary deposit representing colluvial accumulations; common in the Broome area and northwards.

The un-named Pleistocene units in the region that crop out at the coast and locally influence coastal form in that they form cliffs or local headlands, or are stratigraphic markers, or crop out along the interface between the red sand dune plain and the Holocene sediments are:

1. various bioclastic, or oolitic calcarenitic and shelly calcarenitic limestones that occur in the southern and central parts of the region;
2. shelly limestone that occurs in the southern and central parts of the region;
3. lithified calcareous palaeosols that occur in the southern and central parts of the region;
4. ironstone conglomerate sheet; a gravel deposit of ironstone clasts; it occurs throughout the region forming a horizon between the Pleistocene Mowanjum Sand and the Holocene units.

At one stage in this study, it was considered that some of the Quaternary calcarenites along the Canning Coast could be referred to the Bossut Formation, and so some effort was expended in determining what constitutes the Bossut Formation. The ensuing text therefore discusses the concept and definition of the Bossut Formation as a lithological and stratigraphic unit and shows how, in time, since its definition, it has been expanded to the extent that it has subsumed the other Quaternary calcareous Formations in the region.

From its type location and description in Samphire Marsh N°.1 (Lindner & McWhae 1961; Johnstone 1961), it appears that the Bossut Formation may be an artificial mixture of lithologies from different Formations as a result of drilling-rig procedures. Johnstone (1961) describes it as calcarenite, calcilutite and some oolite, and stipulates that it underlies "silts and sands" of the tidal flats. In this context, the Holocene carbonate muds and Holocene tidal flat sands had not been assigned to it. Discussions with Murray Johnstone (pers comm., 1995), who undertook the drilling of Samphire Marsh N°.1 clarified that in the endeavour to drill to Mesozoic and older Formations, the drilling rig probably rapidly penetrated Quaternary superficial sediments, and partly indurated sediments and limestones, thereby mixing (in general order from the surface) any Holocene indurated calcilutite and Pleistocene calcilutite, as well as non-oolitic Holocene and Pleistocene calcarenites, Pleistocene coral limestone, Holocene and Pleistocene oolitic calcarenites, and calcrete (the latter in drill chips would also appear as lithified calcilutite). The definition of Bossut Formation appears to have been based on a combination of lithologies that if they had cropped out individually, most probably would have been assigned to separate Formations (*cf.* the various limestones in the Cape Range area, and the various marine and aeolian limestones in the Shark Bay area and Perth Basin coastal area have been assigned Formational status (Logan *et al.* 1970; Playford *et al.* 1976; Hocking *et al.* 1987; Playford 1990; Semeniuk 1995a).

If the Bossut Formation was in fact closely interbedded calcareous and quartzose sandstone, calcilutite, and oolite (*i.e.*, an intercalated suite of these lithologies), then there would be validity to assigning Formational status to such a lithological assemblage. This range of carbonate rock lithologies does occur in the Canning Coast region, but not interbedded – rather they occur as discrete sedimentary bodies, and often in separate discrete geographic and/or topographically-related locations. For example, calcreted oolitic limestone, traceable from the Port Hedland area, just outside the Canning Coast sector, commonly is (topographically) the most landward of a series of limestone belts; non-oolitic calcarenite of Holocene age, which in the geological mapping in the region by Hickman & Gibson (1982), Gibson (1983a, 1983b, 1983c), also has been referred to the Bossut Formation, is (topographically) the most seaward of the limestone belts; partly oolitic calcarenite of Holocene age occurs as lenses and layers in red sand; and semi-indurated calcilutite occurs in embayments (leeward of the non-oolitic calcarenite of Holocene age or in broad stranded embayments) in the most landward part of embayments at levels 1–2 m above HAT.

In the time since 1960, the term Bossut Formation, because of its lithologically very broad and loose definition, has been applied to nearly every calcarenite of Holocene or Pleistocene age, regardless of lithology, along the Canning Coast from Pardoo Creek to Cape Leveque. For instance, the oolitic limestone in the Port Hedland area is a red calcreted limestone of Pleistocene age, and it has been assigned to the Bossut Formation (Hickman & Gibson 1982). Initially, the exceptions were the Chimney Rock Oolite and the North Head Limestone, both of which had been defined from outcrops along the shore of Dampier Peninsula (Brunnschweiler 1957).

Later, however, Towner & Gibson (1983) and Gibson (1983a, 1983b) included the Chimney Rock Oolite and the North Head Limestone as part of the Bossut Formation. While its original definition included only lithified deposits, Hickman & Gibson (1982) extended the Bossut Formation to include unlithified beach ridge deposits on the coastal plain, and Towner (1982) described it as underlying and interfingering with Holocene silt and sand of the tidal flats (a stratigraphic and chronological relationship that implies that it is Holocene in age). Up to this stage of the history of the nomenclature of the Bossut Formation, there had not been any differentiation between Pleistocene and Holocene stratigraphic units, and so the Bossut Formation was assigned to various lithologies of various ages. However, Gozzard (1988) produced a 1:50,000 Environmental Series Geological Map of the Broome – Roebuck Plains area where Bossut Formation was assigned a Pleistocene age, its distribution in the Broome area was mapped, and it was lithologically described as essentially a quartzose and bioclastic calcarenite (though not oolitic). As will be shown later, the unit assigned to the Bossut Formation and mapped by Gozzard (1988) yields radiocarbon dates to show that it is an earlier Holocene coastal deposit.

Thus, from the literature, it appears that various authors have assigned the name the Bossut Formation to units of Pleistocene to Holocene age that vary from well cemented bioclastic calcarenites to poorly cemented bioclastic calcarenites, to well cemented calcreted oolitic calcarenite, to unlithified beach ridges, and calcilutites.

To help resolve this problem in the recognition and definition of Bossut Formation, as it is delineated and mapped along the Canning Coast, I have visited every major outcrop as well as the type sections of the Quaternary limestone Formations that occur along the coast or near-coastally from Shark Bay to Cape Range in the Carnarvon Basin, from Onslow to Port Hedland along the Pilbara Coast (Semeniuk 1993b, 1996), and from Pardoo Creek to Cape Leveque in the Canning Basin to obtain comparative and reference type section data on limestone Formations in this subcontinental region of Western Australia. This provided information to clarify what constitutes the Bossut Formation, what is its stratigraphy in locations where limestones have been assigned to Bossut Formation (*e.g.*, the Port Hedland 1:250,000 Geological Sheet; Hickman & Gibson 1982), what other limestone Formations are similar to the Bossut Formation, and to what other Formations could Quaternary limestones of the Canning Coast be referred.

On another point in relation to separating Quaternary limestone and sediment types as Formations: to reconstruct Quaternary coastal history and to assist in palaeo-sedimentological and palaeogeographic interpretations and reconstructions, there is a need to separate calcarenites from sands, and also, if they form distinct sedimentary bodies thick enough to be mapped, calcilutites from calcarenites and sands. On these bases, if the Bossut Formation consists of mixed lithology generated by drilling procedures, then the various limestones and sediments that are lithologically distinct, that are thick enough, and that can be mapped regionally should be formally separated and named.

From these considerations presented above, I conclude that the Bossut Formation has too broad a definition, too complex a history of misapplication, and is now too encompassing of a variety of lithologies to be a useful unit at Formation level and is not applied to any stratigraphic units in this paper. A more detailed history of the use of the term Bossut Formation, and its implications, will be presented in a later study.

The various modern coastal types

The various styles of coastal sedimentation, which form the bases to identifying various sedimentary bodies and their earlier Holocene analogues, occur in different types of coast (or coastal environments), from high energy to low energy. These are described first to provide a context for the description of the sediments and sedimentary processes and the Holocene stratigraphic sequences. Modern coastal environments along the Canning Coast are broadly of four types, ranging from the most exposed and eroded to the most protected:

1. rocky shore areas where Mesozoic to Tertiary bedrock and semi-indurated desert sand dunes are exposed;
2. rocky shore areas of Quaternary limestone;
3. sand-dominated flats and beaches/dunes that occur along the open coasts; and
4. mud-dominated environments that occur in the various embayments, lagoons and bays.

Using these four basic coastal types, regionally, the coastal zone can be divided geomorphically into five broad tracts (Figures 4, 5 and 6). The bases of this subdivision are whether there is Mesozoic or Tertiary rock outcrop, Quaternary limestone barriers, sandy barrier dunes and curving beaches, and embayments, and the extent that they are distributed along the coast. The ultimate control of the coastal forms, however, is hinterland geology and geomorphology.

Tract 1: the northern tract is the west coast of Dampier Peninsula (a large peninsula of Mesozoic and Tertiary rock and Quaternary red sand; Geological Survey of Western Australia 1975), and extends from Broome to Cape Leveque; it has a variable shore that consists of exposed Mesozoic and Tertiary rock, Quaternary limestone, and protected embayments, lagoons and bays located within embayments, with Quaternary limestone and barrier dunes emanating from headlands of these embayments. In this tract, there are also small creeks that directly debouche onto the open coast (see Figure 5B) and their mouths are variably barred or partly barred with barrier or north-migrating recurved spits.

Tract 2: the Roebuck Bay coast, situated between Thangoo and Broome, is a large lowland area (now an embayment) located at the junction between the geological units that underlie Tracts 1 and 3. Its northern border is Mesozoic rocks and Quaternary desert dunes of the Dampier Peninsula; its eastern margin is the linear dune field of the northern Great Sandy Desert (where the corridor of low land continues); and its southern margin is the uplands of Mesozoic rock and Quaternary desert dune terrain that are the continuation of the linear trend of the Edgar Range and Hall Range.

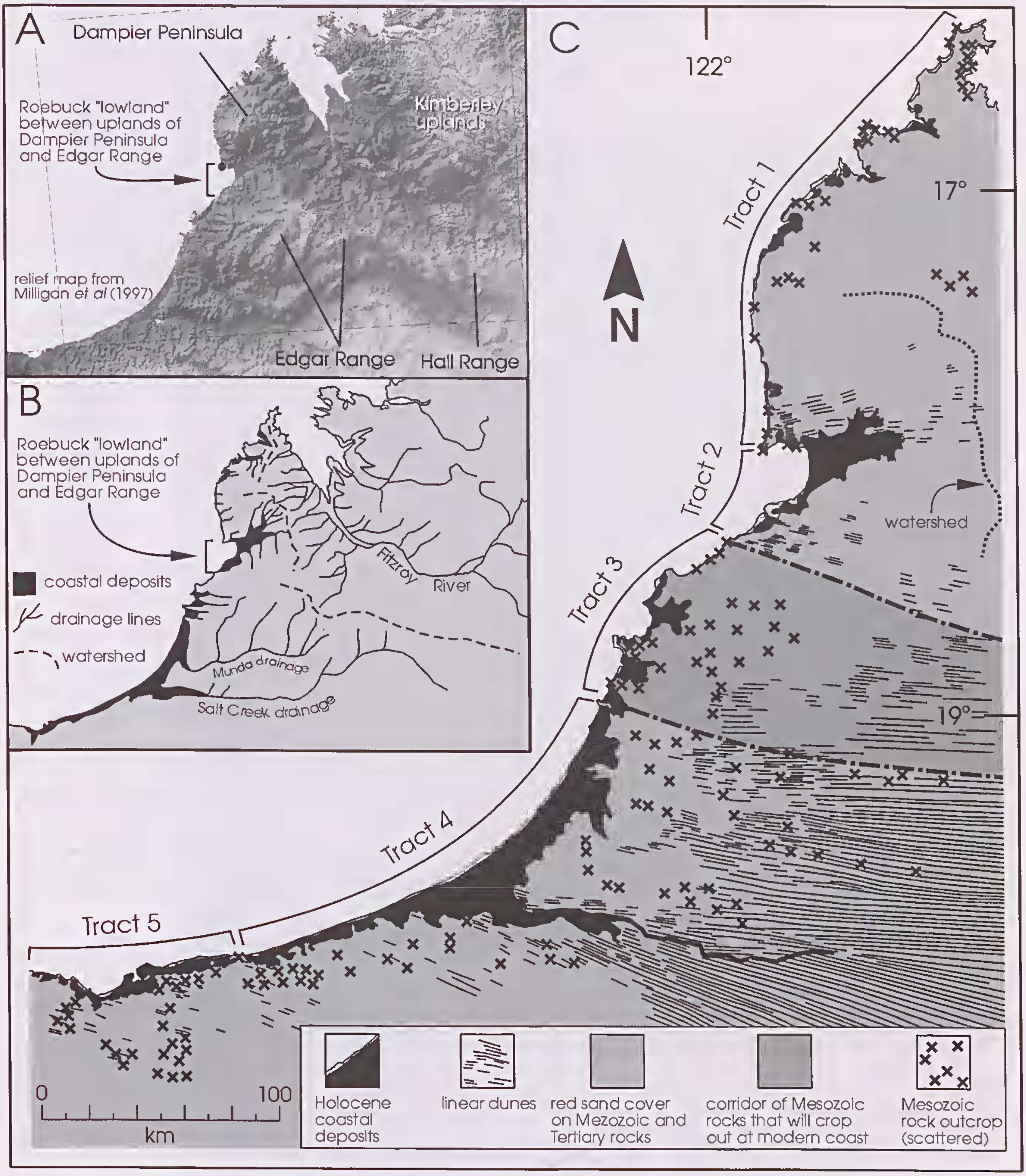
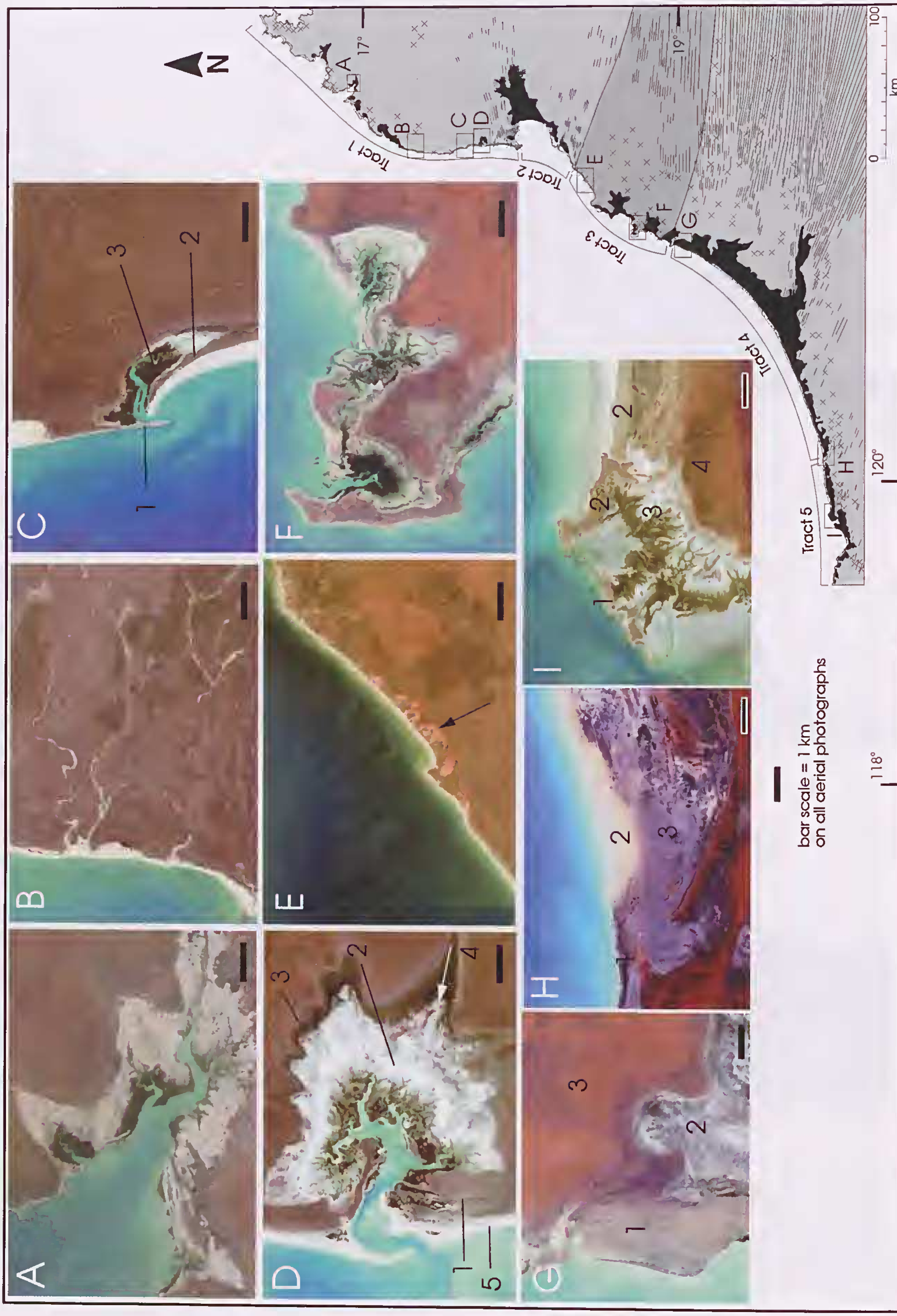


Figure 4. Regional framework for the Canning Coast. A. Relief map from Milligan *et al.* (1997) showing the physiography that underpins the form of the Canning Coast. B. Major and minor drainage lines and uplands that control the form of the Canning Coast; the watersheds show that the Fitzroy River and King Sound system are unrelated to the Canning Coast. C. The five coastal tracts and the distribution of Holocene coastal sediments within the regional framework of the Coast, *i.e.*, the generalised outcrops of Mesozoic rocks, the linear dunes and their orientations, the corridor of Mesozoic rocks that are the extension of the Edgar Range, and the distribution of Holocene coastal sediments; information on outcrops and dune orientations are summarised from geological maps (Brunnschweiler 1957; Johnstone 1961; Veevers & Wells 1961; Hickman & Gibson 1982; Towner 1982; Gibson 1983a, 1983b, 1983c; Hickman 1983; Towner & Gibson 1983; and Hocking *et al.* 1987), and topographic maps and aerial photographs.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Tract 3: this is the northern part of the central main portion of the Canning Coast, located between Desault Bay and Thangoo. It also is the edge of the Great Sandy Desert where it interfaces with the Indian Ocean, but is more irregular, having occurrences of low outcrops of Mesozoic rock interspersed with Tertiary rocks and Quaternary limestone and desert dune sediments. The Mesozoic rocks are the physiographic extension of the Edgar Range. The Mesozoic rock crops out irregularly at the coast, and the outcrops act as headland anchors to coastal development (e.g., to initiate development of recurved barriers), and form zones of protection to coastal sedimentation in embayments. Thus, the coastal zone here consists of local Mesozoic bedrock outcrops, Quaternary limestones (lithified recurved barriers), modern barrier dunes, and truncated desert linear dunes exposed at the coast. Consequently, this tract is comprised of numerous small embayments, lagoons and bays, alternating with headlands, with modern and lithified dune barriers emanating from the headlands.

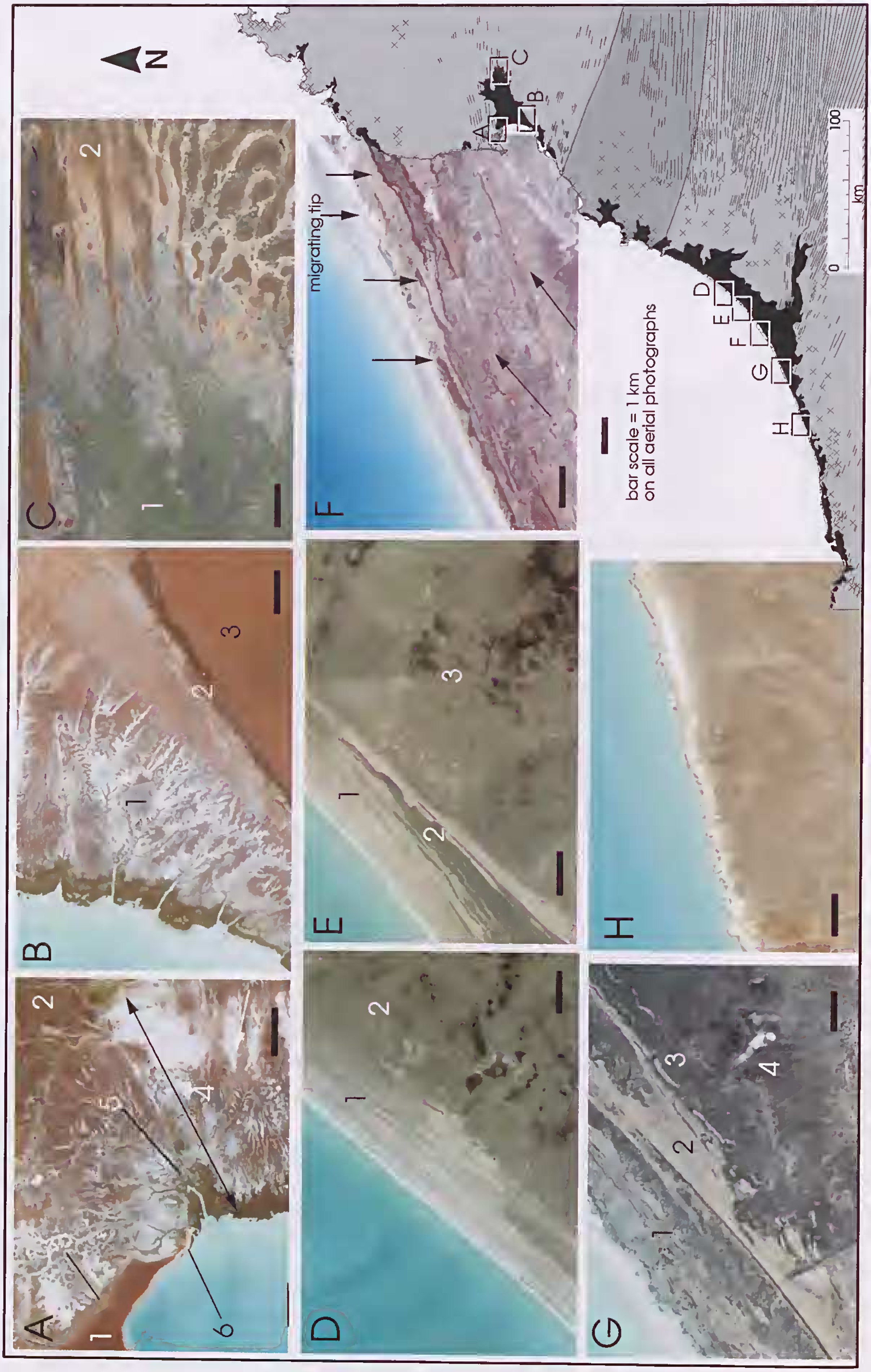
Tract 4: this is the main part of the sector of coast geographically known as Eighty Mile Beach, located between Shoonta Hill and Desault Bay. Fundamentally, it is the seaward edge of former riverine channels, broadly funnel-shaped at their mouths, that have been filled with carbonate mud and have been blocked by Quaternary barrier dune development to form a prograded plain. Currently, the shore is comprised of a barrier dune. While today it is a broadly curved coast, in detail it is composed of dunes, beaches, shore-parallel muddy lagoons, and shore-eroded limestone ridges. The coast is the seaward edge of a retreating prograded plain, which inland is composed of a variable series of stranded units, *viz.*, stranded shore-parallel muddy lagoons, shore-parallel narrow sandy barriers, shore-parallel narrow limestone (formerly sandy) barriers, and chenier plains. The modern eroding edge of the coastal plain is commonly barrier dune perched on a mud sheet deposit.

Tract 5: the southernmost tract, between Pardoo Creek and Shoonta Hill, borders a hinterland of linear dunes and low Mesozoic bedrock outcrops, formed at the edge of the Great Sandy Desert where it interfaces with the Indian Ocean. It is a broadly curved coast, interrupted locally by rocky headlands and outcrops of limestone. As such, the coastal zone here is composed of dunes, beaches, and shore-parallel limestone ridges.

In all five coastal tracts, hinterland drainage is subdued, and hence there is little or no fluvial input to the coast, in comparison to the adjoining coastal sectors of King Sound and the Pilbara Coast, where rivers deliver substantial quantities of terrigenous mud (as kaolinite clay) to the coast (Semeniuk 1993a). Consequently, along the Canning Coast, in appropriate low energy settings such as protected lagoons and bays, marine-derived carbonate muds dominate mid- to upper-tidal environments, *i.e.*, terrestrially-derived kaolinite mud is generally absent. Elsewhere, where sediments are sandy, such as in wave-dominated or tidally-reworked environments, or in dunes, quartz sand (derived from the Mesozoic-Tertiary bedrock or reworked from Quaternary desert dunes), makes a strong exogenic contribution to the sediments. Carbonate sand particles are generated by breakdown of shelly invertebrate benthos, or from foraminifera, and depending on the biogenic productivity, and bioclast influx, coastal sandy sediments range from quartz-dominated to bioclast-dominated. Locally, there has been input of ooids, such that the sands may become oolitic.

The two largest former drainage lines in this region are the Salt Creek system (a formally named inland creek system that ultimately ends in the seaward-widening funnel-shaped coastal lowland of Mandora Marsh, or alternatively known as Samphire Marsh; Figure 4B), and the Munda drainage system (a previously un-named drainage system that comprises the Munda wetland system further inland, *i.e.*, the Munda Claypan and Munro Springs areas, but that can be traced intermittently to the seaward-widening, funnel-shaped coastal lowland marsh at Anna Plains). These are relict channel forms and drainage basins that may extend hundreds of kilometres inland, but today, these drainage lines are buried and/or clogged in their inland tracts, mainly with desert dunes, and in their seaward tracts with marine sediments (mainly carbonate mud). As such, today, they are not functioning as fluvial systems, and from the radiocarbon ages to be presented later in this

◀ **Figure 5.** Aerial photographs characterising the various coastal tracts along the Canning Coast (details of Tracts 2 and 4 are presented in Figure 6). A. Beagle Bay showing funnel-shaped embayment (largely filled with carbonate mud), with scalloped (or multiply cuspate) margins resulting from marine incursion into and sedimentation within the small creek lines. This funnel-shaped embayment does not have a major headland barrier system. B. Middle west coast of Dampier Peninsula showing a range of small creeks entering the coast; their mouths are generally barred by wave-generated small spits and barriers. C. Cape Boileau, a coastal lagoon barred by a ridge of Pleistocene limestone (1), by a Holocene limestone barrier (a dune barrier earlier in the Holocene), and a modern barrier dune (2); tidal flat carbonate muds are accumulating within the lagoon (3). The seaward edge of both the limestone barrier and the modern barrier form a "J"-shaped bay with respect to the Pleistocene limestone ridge. D. Willie Creek, within which, in contrast to Beagle Bay, a Holocene limestone barrier (1) bars an embayment (2) wherein tidal flat carbonate muds are accumulating; the margins of the embayment are scalloped (or multiply cuspate), with a transition zone (3) where sand of the hinterland and mud of the tidal flat interface; locally there are small creeks (white arrow labelled 4) where high tidal alluvial fans have formed (*cf.* Semeniuk 1983, 1985); the shoreward zone is a beach backed by dunes (5). E. Cape Gourdon area where Mesozoic rocks and Mowanjum Sand crop out at the coast; the reworking of Mowanjum Sand by onshore winds has generated landward ingressing red sand dunes (arrowed). F. Cape Bossut area where there is a complex of small embayments partly or nearly completely barred by Holocene limestone barriers; tidal flat carbonate mud accumulates within the embayments. G. South of the Frazier Downs embayment, this area is the northernmost part of Eighty Mile Beach and the beginning of the system of beachridges, narrow barriers, protected muddy tidal flats and lagoons, and chenier plains that characterise Tract 4; here, coastal dunes (1) have formed a beachridge plain, barring a carbonate mud filled embayment (2) that has been cut into the red sand hinterland (3). More details of Tract 4 are provided in Figure 6. H. Shoonta Hill area, the southernmost part of Eighty Mile Beach and the extremity of the system of Tract 4; here, Holocene limestone crops out at the coast (1), modern dunes are developing a barrier (2), barring the carbonate mud sedimentary system (3), and Pleistocene dunes and limestone (4) crop out further inland. I. Cape Keraudren area where a barrier ridge of Pleistocene limestone crops out at the coast (1); this has been instrumental in developing the Holocene barriers (= 2; now limestone), which protect carbonate mud deposits that have onlapped a red sand hinterland (4).



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paper, do not appear to have functioned as riverine systems for the whole,of the Holocene. Information, from inland sites, *e.g.*, the Salt Creek area, inland from Mandora Marsh, and the Munda Claypan and Munro Springs areas, inland from Anna Plains, also suggests that these drainage lines were not active as major fluvial channels even during the Pleistocene. Their relict seaward-widening valley tracts, however, had major influence on the sites of low-energy carbonate mud accumulation during the Holocene.

Roebuck Bay is often viewed to be a former estuary, and has been considered by some perhaps to have been a former outlet of the Fitzroy River. The geomorphic, stratigraphic, and clay mineral sedimentologic evidence, however, is contrary to this notion. The Fitzroy River carries a distinctive signature in terms of its gulf landforms, Quaternary stratigraphy, and clay mineralogy (Semeniuk 1980; 1981a, 1981b, 1993a). Roebuck Bay, if it were to have been a former outlet for this river should carry the same signature, but the stratigraphy of marine sand and carbonate mud filling the embayment, the ubiquitous nature of the Mowanjum Sand as a basal Quaternary unit, and the position of the watershed on the Dampier Peninsula suggest that the embayment was not part of a distributary of the Fitzroy River, but rather a lowland, erosionally carved out between two physiographic regions, *viz.*, the Dampier Peninsula and the Edgar Range (and its western extension) (Figure 4B).

Small creeks have had an influence on coastal form throughout the region. As mentioned above, some small creeks deriving from the Dampier Peninsula reach the open coast and are partly to fully barred, and produce a distinctive type of coast. Elsewhere, small creeks and their associated shallow valleys, when flooded by the early Holocene post-glacial transgression, were on-lapped and filled by Holocene sediments, which resulted in the development of scalloped (or multiply cuspate) margins to embayments (Figures 5A, 5D and 5F).

Holocene sedimentary accumulations

Holocene sediment accumulations along the Canning Coast have occurred, and currently occur, in a number of settings. They are related to the extent that the coast was and is exposed to prevailing wind and waves, and to the extent that embayments are indented and oriented to be protected from high energy coastal processes (wave and wind action; Figures 4, 5 and 6). In this section there is separation of earlier Holocene settings and modern (and sub-recent) Holocene settings, as earlier Holocene sedimentation created barriers that influence development of current (*i.e.*, modern and sub-recent) sedimentation.

The earlier Holocene settings

Earlier Holocene sedimentary settings that were host to sedimentary accumulations or that influenced development of sedimentary accumulations are the rocky shores and headlands cut into Mesozoic rock and Quaternary desert dune terrain, the embayments cut into Mesozoic rock and Quaternary desert dune terrain, the broad (embayment) lowland of the ancestral Roebuck Plains, and the valley tracts of the Salt Creek drainage system and Munda drainage system that end in the Mandora or Samphire Marsh, and in the Anna Plains area respectively.

The later Holocene settings

Modern and sub-recent sedimentation is taking place in coastal settings that, in part, are founded on coasts cut into Mesozoic rock and Quaternary desert dune terrain, as described above, but also in coastal settings that are derived from earlier coastal sedimentation, *e.g.*, mud in embayments has shoaled to form coastal plains, and accumulation of sand to form barriers at the headlands and mouths of embayments.

From high energy to relatively low energy, these sedimentary settings are:

1. open coastal, high energy environments where there is erosion of older Quaternary (Pleistocene) linear red sand dunes, with perching of Holocene white coastal dune sands, and intermixing of (Holocene) white sand and red sand in the zone of inter-fingering of the reworked Pleistocene dunes and Holocene dunes;
2. open coastal, high-energy sand-dominated environments wherein accumulates a spectrum of facies from sandy and shelly sand low-tidal sediments, beach sediments and coastal dune sands;
3. open coastal, high-energy barrier-and-lagoon environments, composed of multiple shore-parallel linear dune barriers; the facies encompass sandy and shelly sand low-tidal sediments, beach sediments, and coastal dune sands, and to leeward of the

◀ **Figure 6.** Aerial photographs showing details of Tracts 2 and 4 along the Canning Coast. A–C are of Roebuck Bay. A. Northern Roebuck Bay where there is a headland ridge of Mesozoic rock with cover of red sand (1), red sand of hinterland (2), with a transition zone (3) where red sand and mud of the tidal flat interface, mid to high tidal carbonate mud flat (4), Crab Creek as a geographic feature (5), and spit (6) emanating from headland. B. Southern Roebuck Bay with tidal creeks dissecting the mid to high tidal carbonate mud flat (1), a transition zone (2) where sand of the hinterland and mud of the tidal flat interface, and a hinterland of red sand (3). C. Eastern margin of Roebuck Plain where stranded carbonate mud flats (1) onlap and bury the linear red dunes of the hinterland (2). D–H are of central Eighty Mile Beach that is characterised by a system of beachridges, narrow barriers, protected muddy tidal flats and lagoons, and chenier plains. D–G show a north to south transition in configuration of beachridges, narrow barriers, and mud-filled lagoons. D. Beachridges form a stacked system (1) seaward of a stranded mud flat (2). E. Further south, beachridges begin to separate with development of mud-filled swales (2); the beachridge system occurs seaward of a stranded mud flat (3). F. Beachridges (arrowed) are widely separated, with intervening mud-filled swales; their morphology and relationship to the mud-filled swales suggests they have formed as shore-parallel spits that, when emerged, are the nuclei for a barrier dune; currently migrating recurved tips of a shore-parallel spits are labelled. G. A complex of barriers and intervening stranded mud flats (1), a barrier comprised of beachridges (2), a chenier plain (of cheniers and intervening stranded mud flats = 3), and the oldest part of the Holocene system, a stranded mud flat (4). H. Southernmost part of Tract 4 where a Holocene limestone ridge crops out at the coast; coastal erosion results in a scalloped limestone shore.

barriers, lagoons which, at levels of mid-tidal to high-tidal, are underlain by carbonate muddy sediments;

4. open coastal, high-energy barrier-and-lagoon environments, composed of a single linear dune barrier anchored at a rocky headland; the facies range from low-tidal sediments such as sandy and shelly sand, beach sediments, and coastal dune sands, and to leeward of the sandy barriers, lagoons which, at levels of mid-tidal to high-tidal zones, are underlain by carbonate muddy sediments;
5. protected to semi-protected embayments (bordered by rocky headlands of Pleistocene limestone or Mesozoic bedrock), wherein sand accumulates in the low-tidal zones and carbonate muddy sediment accumulates in mid- to upper-tidal zones, with modern spits or dune barriers emanating from the headlands.
6. protected to semi-protected embayments (bordered by rocky headlands of Pleistocene limestone or Mesozoic bedrock), wherein sand accumulates in the low-tidal zones and carbonate muddy sediment accumulates in mid- to upper-tidal zones, with an absence of modern spits or dune barriers emanating from the headlands.

Particles and components of the sediments

Particles that comprise the sediments of the Canning Coast vary in grainsize and composition, and in their origin. In grainsize, they vary from boulder-sized to mud-sized material and include: boulder, cobble, to pebble-sized intraclasts (derived from eroding beachrock) or lithoclasts (derived from Mesozoic rocks or Pleistocene rocks); gravel sized shells and shell fragments; sand-sized bioclasts mainly of molluscs and echinoderms; sand-sized foraminifera; sand-sized intraclasts, lithoclasts, ooids (with oolitic envelopes on centres of sand-sized quartz, bioclasts, foraminifera, intraclasts, or lithoclasts), clean quartz sand; quartz sand that is coated with iron oxides and fine-grained silt and clay; mud-sized carbonate particles; kaolinitic clay; and silica particles such as quartz silt, sponge spicule fragments, diatoms, and radiolarians. The sediments of the Canning Coast thus varying from being carbonate dominated to being siliciclastic. A selection of particle types is illustrated in Figure 7. The illustrations in Figure 7 have been organised to show the range of particle sizes from boulders to mud-sized (Figure 7A to Figure 7R), and in addition, the lithological/petrographic range of calcarenites to sands, drawn from early Holocene units to modern dune, beach, and low-tidal sands, and from the southernmost part of the Canning Coast (modern dune and beach sand at Pardoo Creek, and calcarenite at Shoonta Hill) to nearly the most northernmost part (modern dunes at Camp Inlet). In the caption to Figure 7 the various dominant, or most abundant, or conspicuous carbonate sand components of the photomicrographs are comprehensively listed, but not directly individually identified and annotated on the photomicrographs. The reader is referred to carbonate petrographic texts such as Majewske (1969), Bathurst (1975), Flugel (1982) if more specific identification of the particles is required.

Fossils and subfossils, such as molluscs and foraminifera, reworked from older Holocene Formations, or from contemporary lithified Formations, are variably preserved as particles, from whole tests to fragments often with cemented matrix adhering. Molluscs and foraminifera also occur as steinkerns (*e.g.*, Figure 7O).

It is beyond the scope of this paper to describe and discuss the origin of the particles that comprise the sediments of the Canning Coast; this will be the subject of a later study. At this stage, it is worthwhile to note that the carbonate mud that dominates the intertidal zone of protected environments is exogenic (composed of marine-derived particles), that there is much reworking and recycling of sediments of all particle sizes along the coast, that the bioclast to quartz ratio within each of the Holocene Formations is variable, and that ooid to quartz ratio in the sediments also is variable both along the coast and within the stratigraphic sequence at any given locality.

Mollusc shells dominate the fossil, subfossil, and extant shelly fauna of the Holocene Formations and sediments of the Canning Coast, contributing gravel as whole and fragmented shells, and sand-sized particles as shell fragments to the sediment. The molluscs encountered in this study as fossil and subfossil shells are listed in Table 3. There are at least 80 species of bivalve and 60 species of gastropod encountered in this study. Other fauna such as crustaceans (decapods and barnacles), echinoderms, corals, polychaetes, and bryozoans are not abundant enough, do not preserve well, or are not consistently preserved enough for detailed study in this paper. While dominating the fauna, mollusc shells themselves, however, exhibit various stages of preservation, from recently dead (and morphologically intact, with shell colour) to long-term dead (and fragmented, or abraded and without colour), to those embedded in calcarenites (and are colourless, and/or abraded, and/or solution-corroded).

Modern sedimentary processes and products

Various sedimentary processes operate at various scales along the Canning Coast, and these result in a diversity of sedimentary bodies and sediment types. The processes operating to generate large-scale sedimentary bodies and sediment types are prevailing wave action, storm waves and storm surge, tide action, aeolian activity, and local fluvial discharge.

Prevailing wave action, through erosion, transport and sedimentation, generates, maintains, and accretes beaches, spits, cheniers, and sand shoals as coastal geomorphic units, and generates well winnowed sands, gravelly sands and shell gravel as sediment types. Storm waves, with higher seas and storm surge, massively erode and rework sediments along the coast. Sandy beaches may be stripped of sand, leaving intraclast and lithoclast gravel or shell gravel lags. For example, following a cyclone that crossed the coast near Broome, parts of Cable Beach, a sand-dominated beach north of Broome, were reduced to a sandstone and ironstone lithoclast gravel bed resting on Mesozoic bedrock. In addition, shell lag deposits are formed on tidal mud flats,

Table 3

Fossil and subfossil molluscs encountered in this study (in alphabetical order)

Bivalves

Acrosterigma fultoni (Sowerby, 1916), *Acrosterigma* cf. *fultoni* (Sowerby, 1916), *Acrosterigma reeveanum* (Dunker, 1852), *Acrosterigma vlamingi* Wilson & Stevenson, 1977, *Anadara crebricostata* Reeve, 1844, *Anadara granosa* (Linnaeus, 1758), *Anadara secticostata* (Reeve, 1844), *Anadara* sp. Gray, 1848, *Anomalocardia squamosa* (Linnaeus, 1758), *Antigona* cf. *chemnitzii* (Hanley, 1844), *Antigona chemnitzii* (Hanley, 1844), *Arca avellana* Lamarck, 1819, *Arca ventricosa* Lamarck, 1819, *Asaphis* sp. Modeer, 1793, *Asaphis violascens* (Forsskal, 1775), *Austriella sordida* Tenison Woods, 1881, *Barbatia* cf. *coma* (Reeve, 1844), *Barbatia coma* (Reeve, 1844), *Barbatia foliata* (Forsskal, 1775), *Callista impar* (Lamarck, 1818), *Cardita* cf. *preissii* Menke, 1843, *Cardita incrassata* Sowerby, 1825, *Chama reflexa* Reeve, 1846, *Chama* sp. 1 Lamarck, 1809, *Donax faba* Gmelin, 1791, *Donax* cf. *faba* Gmelin, 1791, *Donax* sp. Linnaeus, 1758, *Dosinia deshayesii* A. Adams, 1855, *Dosinia incisa* (Reeve, 1850), *Dosinia scalaris* (Menke, 1843), *Dosinia* sp. Scopoli, 1778, *Eucrassatella pulchra* (Reeve, 1842), *Exotica assimilis* (Hanley, 1844), *Fragum hemicardium* (Linnaeus, 1758), *Gafrarium dispar* (Holten, 1802), *Gafrarium tumidum* Roding, 1798, *Hemidonax arafurensis* Ponder *et al.*, 1981, *Hyotissa hyotis* (Linnaeus, 1758), *Irus* sp. (Schmidt, 1818), *Macoma praetexta* (Martens, 1865), *Mactra abbreviata* cf. *meretriciformis* Lamarck, 1819, *Mactra incarnata* Reeve, 1854, *Mactra westralis* Lamprell & Whitehead, 1990, *Meropesta nicobarica* (Gmelin, 1791), *Mimachlamys scabricostata* (Sowerby, 1915), *Modiolus auriculatus* Krauss, 1848, *Modiolus micropterus* Deshayes, 1836, *Modiolus* cf. *trailii* Reeve, 1857, *Paphia crassisula* (Lamarck, 1818), *Paphia semirugata* (Philippi, 1847), *Paphies heterodon* (Reeve, 1854), *Paphies* sp. Lesson, 1830, *Paphies striata* (Gmelin, 1791), *Pinctada maxima* Jameson, 1901, *Pinna bicolor* Gmelin, 1791, *Pitar* sp. Romer, 1857, *Placamen gravescens* (Menke, 1843), *Placuna placenta* (Linnaeus, 1758), *Saccostrea cucullata* (Born, 1778), *Semele jukesii* (Reeve, 1853), *Septifer bilocularis* (Linnaeus, 1758), *Solen kajiyamai* Habe, 1964, *Spondylus wrightianus* Crosse, 1869, *Sunetta perexcavata* Fulton, 1915, *Tapes literatus* (Linnaeus, 1758), *Tellina capsoides* Lamarck, 1818, *Tellina piratica* Hedley, 1918, *Tellina* cf. *piratica* Hedley, 1918, *Tellina rostrata* Linnaeus, 1758, *Tellina virgata* Linnaeus, 1758, *Tellina* sp., *Trachycardium flavum* (Linnaeus, 1758), *Trisidos semitorta* (Lamarck, 1819), *Trisidos tortuosa* (Linnaeus, 1758), *Venus lamellaris* Schumacher, 1817, unidentified Cardiid, unidentified Mesodesmatid, unidentified Pectinid, unidentified Venerid

Gastropods

Amalda elongata Gray, 1847, *Astraea rotularia* Lamarck, 1822, *Bulla ampulla* Linnaeus, 1758, *Bulla guoyii* Gray, 1843, *Calthalotia strigata* (Adams, 1853), *Cantharus* cf. *erythrostoma* (Reeve, 1846), *Cassidula angulifera* Petit, 1841, *Cerithidea anticipata* Iredale, 1929, *Cerithidea* cf. *cingulata* (Gmelin, 1791), *Cerithidea cingulata* (Gmelin, 1791), *Cerithidea reidi* Houbrick, 1986, *Chicoreus cornucervi* (Roding, 1798), *Chicoreus permestus* Hedley, 1915, *Chicoreus rubiginosus* Reeve, 1845, *Chicoreus ryosukei* Shikama, 1978, *Chicoreus* sp., *Cominella* cf. *lineolata* (Lamarck, 1809), *Conus* sp., *Conus textile* Linnaeus, 1758, *Conus trigonus* Reeve, 1848, *Conus victoriae* Reeve, 1843, *Cronia aurantiaca* Hombron & Jaquinot, 1835, *Cymatium vespaceum* (Lamarck, 1822), *Cymatium waterhousei* (A. Adams & Angas, 1865), *Cypraea gracilis* Gaskoin, 1849, *Cypraea pyriformis* Gray, 1824, *Duplicaria duplicata* Linnaeus, 1758, *Ellobium aurisjudae* Linnaeus, 1758, *Epitonium imperialis* Sowerby, 1844, *Ficus eospila* (Peron-Lesueur, 1807), *Fusinus colus* (Linnaeus, 1758), *Herpetopoma atrata* Gmelin, 1791, *Littoraria* cf. *cingulata* (Philippi, 1846), *Melo amphora* Lightfoot,1786, *Murex macgillivrayi* Dohrn, 1862, *Murex* cf. *acanthostephes* Watson, 1883, *Nassarius dorsatus* Roding, 1798, *Naticarius alapapiliones* Roding, 1798, *Nerita squamulata* Le Guillou, 1841, *Nerita undata* Linnaeus, 1758, *Neritina* cf. *violacea* (Gmelin, 1791), *Oliva lignaria* Marrat, 1868, *Phalium areola* Linnaeus, 1758, *Phasianella australis* Linnaeus, 1758, *Planaxis sulcatus* (Born, 1780), *Polinices conicus* (Lamarck, 1822), *Polinices* sp., *Pyrene varians* (Sowerby, 1832), *Pythia* cf. *scarabaeus* (A. Adams), *Stramonita javanica* (Philippi, 1848), *Strombus campbelli* Griffith & Pidgeon, 1834, *Syrinx aruanus* Linnaeus, 1758, *Tectus fenestratus* Gmelin, 1791, *Telescopium telescopium* Linnaeus, 1758, *Terebralia palustris* Linne, 1767, *Terebralia sulcata* (Born, 1778), *Trochus maculatus* Linnaeus, 1758, *Turbo bruneus* Roding, 1791, *Turbo laminiferus* Reeve, 1849, unidentified Marginellid, unidentified Trochid

cliffs are cut into tidal mud deposits, beach rock is disrupted and beachrock slabs are undercut, lifted, and transported shoreward, and cliffs are cut into dune faces. Tide action, through erosion, transport and sedimentation, generates tidal flats, tidal creeks, spits and cheniers, megaripples, and sand shoals as coastal geomorphic units, and (generally) sands and muddy sands, gravel lags on tidal flats, and mud as sediment types. Aeolian action, through erosion, transport and sedimentation, generates dunes and supratidal sand flats as coastal geomorphic units, sand dunes and sand sheets, and gravel lags on sand flats as sediment types. Local fluvial discharge involves sheet wash and creek flow. Sheet wash, during the monsoonal period, delivers sands and kaolinitic mud to the high-tidal margins and supratidal margins of tidal sedimentary zones. Local creek flows, also during the monsoonal period, deliver sands and kaolinitic mud into discrete high-tidal alluvial fans at the heads of embayments (Semeniuk 1985); these alluvial fans inter-finger with sediments of the tidal and supratidal zones.

At the medium and small scales, there is a plethora of physical, hydrological, hydrochemical, and biogenic processes and products that result in various sedimentary surfaces (small-scale geomorphic features) and sediment types (Semeniuk 2005). Physical processes result in sedimentary products such as: rippled sediments (ripple laminated structures) under wave action and tidal action; the formation of sedimentary layering through swash action, tidal current transport and deposition, or aeolian action; bubble sand formed under conditions of wave run-up and a rising water table with a rising tide; and grain fragmentation and rounding under wave action. During storms, there is reworking and brecciation of rock slabs or crusts, and development of shell concentrates through winnowing which, when later buried under more quiescent conditions, exist as buried shell beds. Exposure of sediment to wind and sun results in desiccation and cracking of mud, which later, through reworking generates mud clast breccia and mud fragment sand. Hydrological and hydrochemical processes result in beachrock (the local cementation of

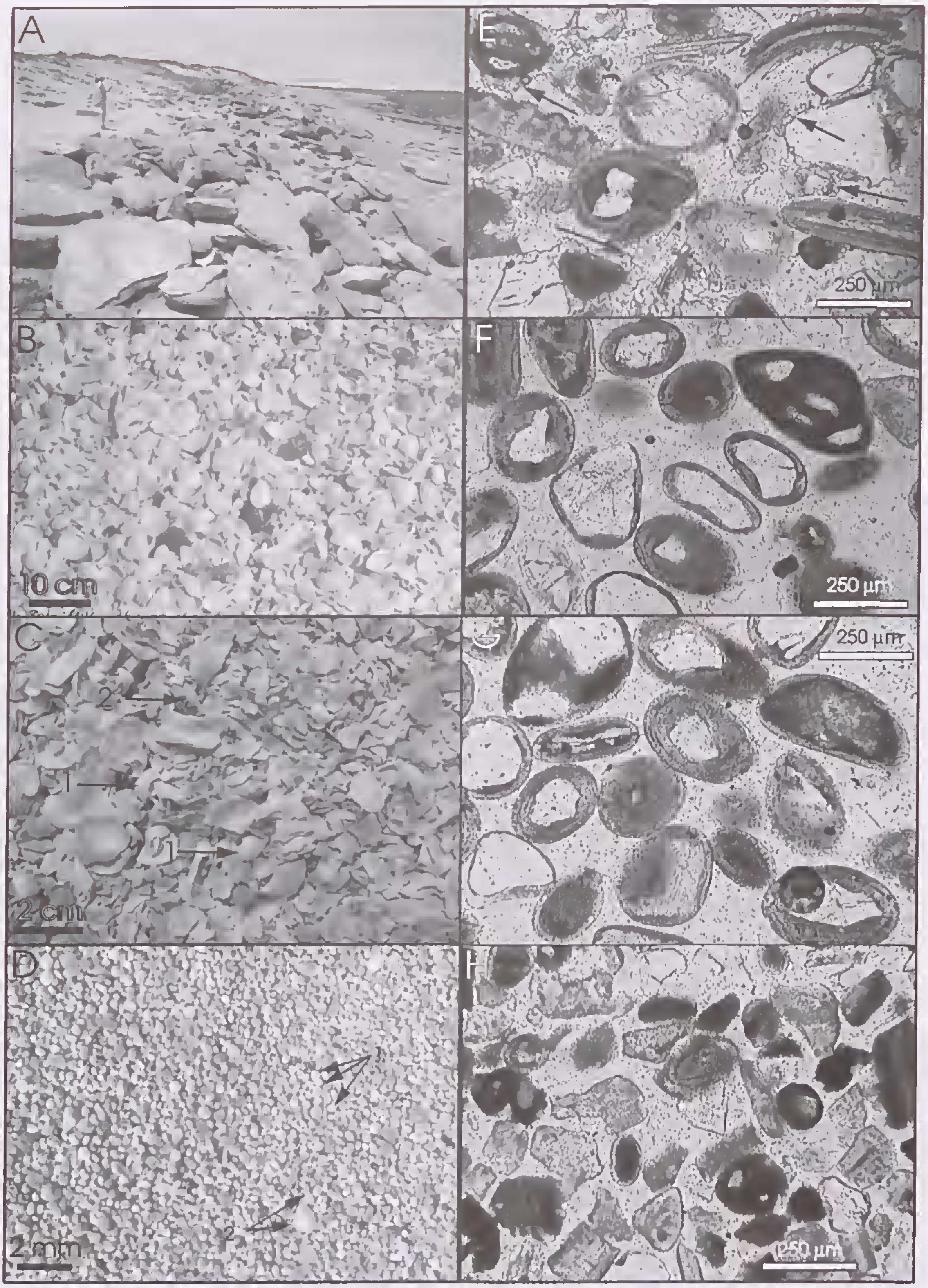
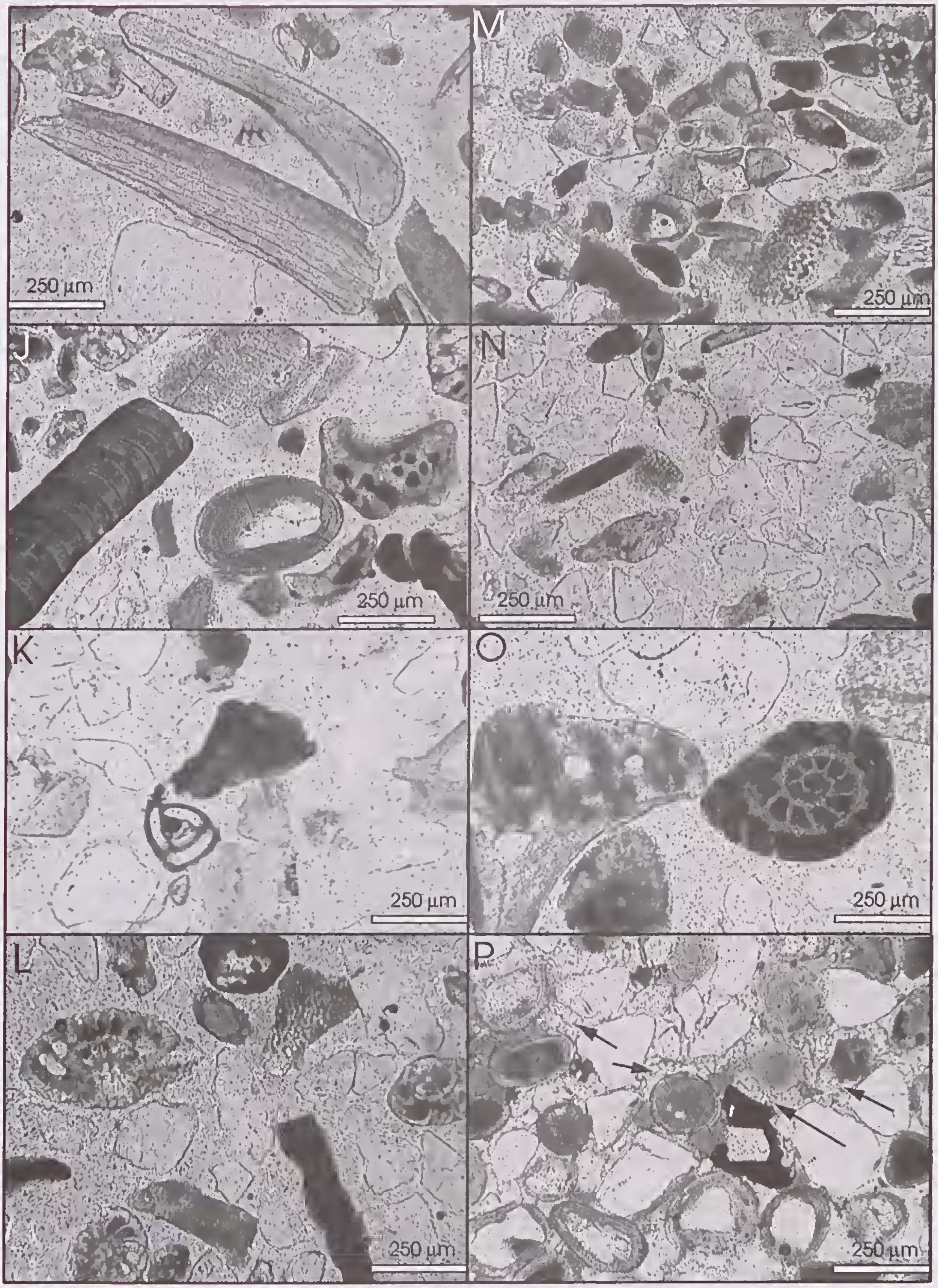


Figure 7. The range of particle sizes, from large to small, and petrography of sediments of the Canning Coast. All bar scales for E–P are 250 µm. A. Boulder-sized intraclasts reworked by storms from beachrock from the Lombadina Conglomerate Member. B. Polymictic shell concentrate formed by winnowing of beach shorefaces during storms from the Eighty Mile Beach Coquina C. Monomictic shell gravel composed dominantly of fragmented oysters (*Saccostrea cucullata*) with rarer *Cerithidea* sp (arrow 1) and *Nerita* sp (arrow 2) reworked from mangrove environment, and concentrated into cheniers by storms from the Race Course Plains Coquina. D. Grains comprising Holocene calcareous quartz sand, composed mainly of orange-stained quartz, with about 10% carbonate grains (ooids, with some examples arrowed as 1, and bioclasts, with some examples arrowed as 2) from the Barn Hill Formation. E–P. Photomicrographs of thin sections of various Holocene calcarenite and sand lithologies under plane polarised light. E. Kennedys Cottage Calcarenite at Port Smith showing oolitically coated molluscs, quartz, foramenifera and lithoclasts, and echinoderm fragments. Not all sand grains are oolitically coated. Interstitial grain-rimming sparry calcite cement is arrowed. F & G. Port Smith Sand at Port Smith showing oolitically coated molluscs, quartz, foramenifera and lithoclasts. H. Shoonta Hill Sand at central Eighty Mile Beach showing foramenifera, molluscan bioclasts, quartz, echinoderm fragments, carbonate intraclasts, and carbonate lithoclasts.



I. Grit (very coarse sand) from the Cable Beach Sand at Cable Beach showing mollusc fragments and quartz. J. Grit from the Cable Beach Sand at Cable Beach showing mollusc fragments, calcareous alga, other bioclasts, quartz, and oolitically coated quartz. K. Cable Beach Sand at Pardoo Creek showing quartz (which is dominant), foramenifera, intraclast, and mollusc bioclast. L. Shoonta Hill Sand at Pardoo Creek showing quartz, foramenifera, intraclast, echinoderm fragment, and mollusc bioclast. M. Cable Beach Sand at Cable Beach showing quartz, oolitically coated grains, foramenifera, echinoderm fragments, molluscan bioclasts, and carbonate intraclasts. N. Shoonta Hill Sand at Camp Inlet; the sand is dominated by quartz, with some carbonate intraclasts, foramenifera, echinoderm fragments, and molluscan bioclasts. O. Cable Beach Sand at Cape Boileau showing coarse sand of quartz, molluscan bioclast, an echinoderm fragment, and an intraclast with a foraminiferal core (a steinkern). P. Calcarenite from a limestone lens in the Barn Hill Formation showing mainly quartz and ooids. Some examples of interstitial grain-rimming sparry calcite cement are arrowed.

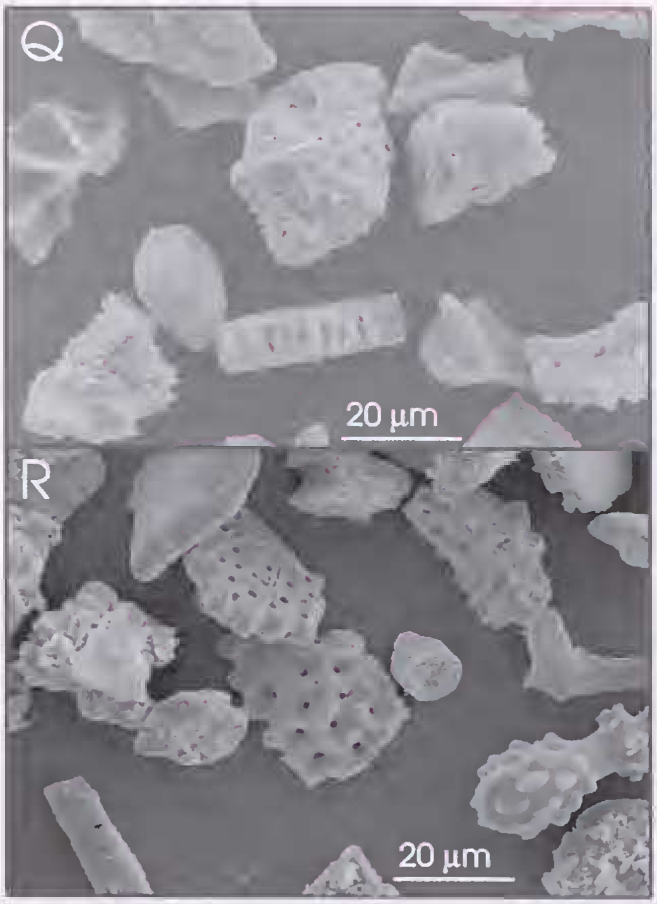


Figure 7. (cont.) Q–R. SEM images of carbonate mud from the Sandfire Calcilutite. Q. Fragments of molluscs, foramenifera, and other bioclasts. R. Fragments mainly of foramenifera and molluscs, with other bioclasts; a sponge spicule is arrowed.

beach sand and shelly beach sand), or solution of shells (e.g., removal of shells from shelly mud), or mineral precipitation. Biogenic processes result in (mangrove and samphire) root-structuring, in-faunal bioturbation, pelletising of the sediment surface by crustaceans, shell generation, shell fragmentation, and sulphide pigmentation of sediment.

Examples of the array of sediments, and the stratigraphic sequence developed in each of these settings are described below for open coastal high-energy environments, open coastal high-energy barrier environments, muddy embayments, lagoons and bays, beach environments, and sites where cheniers are formed.

The open coastal high-energy environments are located along Tract 5, the southern section of the Canning Coast, and Tract 1, the exposed western shore of Dampier Peninsula. The coastal zone in such settings consists dominantly of three sedimentary lithosomes: (1) a low tidal flat grey sand; (2) a mid-high tidal light-coloured beach deposit of sand, or shelly sand, or shell gravel and; (3) a supratidal belt of white dune sand. The quartz component of the sand is derived by erosion of the local bedrock, the local Quaternary limestones, the Quaternary desert dunes, or has been transported from alongshore. The carbonate component of the sand is locally derived bioclasts, foraminifera, and erosion of the local Quaternary limestones. High energy coastlines subject to strong wind action also are locations where red sand of the Quaternary desert dunes are reworked and form shore-parallel (Holocene) red dunes. They may be mixed with or interfinger with white coastal dunes.

The open coastal high-energy barrier environments are located along Tract 4, the southern central section of the Canning Coast (such as Eighty Mile Beach). The coastal zone in such settings consists of four sedimentary lithosomes: (1) a low tidal flat grey sand, a mid-high tidal light-coloured beach deposit of sand, shelly sand, and shell gravel; (2) a supratidal belt of white dune sand and; (3) a mid-high tidal light-coloured carbonate mud deposit. As for the setting described above, the quartz component of the sand is derived by erosion of the local bedrock, local Quaternary limestones, and Quaternary desert dunes, or has been transported from alongshore. The carbonate component of the sand is locally derived molluscan, echinoderm, and bryozoan bioclasts, foraminifera, and erosion of the local Quaternary limestones.

The muddy embayments, lagoons and bays are located in pockets such as at Cape Keraudren, the coastal section between Cape Bossut and Cape Leveque, and in large embayments such as Roebuck Bay. The conspicuous smaller embayments, from south to north are: Cape Keraudren, Lagrange Bay, Cape Bossut, Port Smith, Thangoo, Coconut Well, Willie Creek, Cape Boileau, Pender Bay, Beagle Bay, and Carnot Bay. They exhibit a recurring geomorphic pattern of embayments barred by dunes and limestone ridges. Roebuck Bay and Beagle Bay are large open embayments, without prominent limestone barriers. The coastal zone in such settings consists of three sedimentary lithosomes: (1) a low tidal flat grey sand, or mid-low tidal mud; (2) a mid-high tidal light-coloured carbonate mud deposit, and; (3) locally a (mid-) high-tidal to supratidal shoe-string deposit of shelly sand and shell gravel.

For open high-energy coasts, in the lithosome forming in low-tidal zones, situated between MLWS and *circa* MSL (or locally MLWN), the sand is fine to medium, and has scattered shells derived from the local molluscan fauna. This sand and shelly sand is grey and bioturbated by crustaceans (such as soldier crabs and sand bubbler crabs), molluscs and fish. The shell content is diverse, but scattered. Reworking and transport of the low tidal flat sediments to mid-high tidal zone environments by wave action generates the lithosome in the beach zone.

Beach faces are inclined, winnowed by wave action and tidal currents, and well oxygenated, hence the sediments are laminated to bedded, light coloured medium to coarse (and some fine) sand, shelly medium to coarse sand, shell grit, and shell gravel. Depending on the amount of reworking by waves and storms, and the extent of alongshore and up-slope transport by prevailing waves and storm waves, and the resulting transport and concentration of lag, in some coastal sections the shore zone is shell gravel dominated; in others it is sand dominated. In supratidal zones, there is a shore-parallel dune belt composed of white, fine and medium sand derived by aeolian transport from the beach face. Locally, in the dunes, there are soils and middens. The stratigraphic sequence formed by coastal progradation in this setting consists of grey sand, or shelly sand, overlain by shell gravel, overlain by white dune sand.

For muddy settings, *i.e.*, lagoons behind linear barriers, or in embayments and bays, the lithosome forming in low-tidal zones between MLWS and *circa* MSL (or locally MLWN), is similar to that described for open coasts: it is fine to medium, bioturbated grey sand and shelly sand. Where the influx of carbonate mud is dominant, either from offshore, alongshore or from erosion of onshore deposits, the low-tidal zone between MSL to LAT, or even to the subtidal, may be carbonate mud-dominated, with the formation of extensive carbonate mud flats. However, the accumulation of carbonate mud is generally a feature of low energy mid-high tidal environments. Tidal zones between MSL and HAT are the environments that accumulated carbonate mud under a mangrove and samphire cover. Tidal zones between MLWN and MSL, depending on setting, may also be accumulating carbonate mud and shelly carbonate mud. The bulk of the muddy sediments, however, accumulated in the mangrove environment, forming a bioturbated and root-structured carbonate mud lithosome. The sediments are bioturbated to structureless, and contain scattered shells comprising species indicative of the mangrove assemblage.

Cheniers are commonly located landward of, or within, the mangrove-associated sediment lithotope. They are located in areas of prevailing mud sedimentation that are also subject to periodic wave action during storms and cyclones. Where mangroves are present along muddy coasts, such vegetation may be temporarily removed by natural processes, and there is shoreward transport of shell and sand from low-mid-tidal zones, as well as a concentrating and transport of shells from within the mangrove zone, to the areas within or landward of the mangrove sediment lithotope. These deposits form cheniers that are shoe-string deposits of light-coloured shell gravel and sandy shell gravel accumulated in high-tidal to supratidal levels, respectively. The cheniers can also form within mangrove-vegetated zones, where wave action translates through the vegetation. The stratigraphic sequence containing cheniers formed by coastal progradation in these settings, from low-tidal level to high-tidal level, consists of grey sand, overlain by carbonate mud, with local shoe-string deposits of shell gravel.

Descriptions of the main sediments in each of these coastal settings, in terms of sediment types and derivation, are provided in Table 4. The description focuses on the main sediments in the region that are diagnostic of a given Formation. Since the sediments can vary from carbonate-dominated to siliciclastic, particularly for the sandy sediments, emphasis is placed on grainsize and sedimentary structures; sediment composition is noted where stratigraphically important or relevant within the descriptions and in the definitions of the Formations.

The Holocene stratigraphic units

The criteria for identifying stratigraphic units in this study are lithology and sedimentary structures, but with variable application of these criteria from Formation to Formation. The major criteria are: 1. grain size (*e.g.*, whether the component particles in the sediment or limestone are dominantly mud-sized, sand-sized, gravel-sized, or block-sized, the latter manifest as breccia); 2. sediment colour (*e.g.*, red quartz sand *versus* cream calcarenite); 3. sediment composition (*e.g.*, quartz sand *versus* bioclastic sand; or oolitic grains *versus* bioclastic grains to separate calcarenites; or shelly calcarenite *versus* plain calcarenite); 4. shell composition (*e.g.*, limited species-specific assemblages such as those inhabiting mangrove environment lithotopes *versus* mixed assemblages, such as those inhabiting low tidal flats); and 5. type and scale of sedimentary structures (*e.g.*, large-scale cross-bedding and cross-lamination *versus* horizontally bedded and laminated to low-angle cross-bedded and cross-laminated; whether the sediment is bioturbated, burrow-structured, or root-structured; and whether it contains layers of bubble sand). Sedimentary structures, sediment grainsize, and grain type also were the criteria used to separate the various Holocene calcarenites (*i.e.*, use of lamination, small-scale cross-lamination, large-scale cross-bedding and cross-lamination, the occurrence of carbonate intraclast conglomerates and breccia, the occurrence of bubble sand, burrow structures and bioturbation).

With application of these criteria, twelve new Holocene stratigraphic units were recognised along the Canning Coast; they are:

1. Shoonta Hill Sand
2. Eighty Mile Beach Coquina
3. Cable Beach Sand
4. Port Smith Sand
5. Race Course Plains Coquina
6. Sandfire Calcilutite
7. Cape Gourdon Formation
8. Barn Hill Formation
9. Church Hill Sand
10. Horsewater Soak Calcarenite
11. Kennedys Cottage Limestone
12. Willie Creek Calcarenite

Two members are described within the Cable Beach Sand; they are:

1. Lombadina Conglomerate Member
2. Cape Boileau Calcarenite Member

Three members are described within the Sandfire Calcilutite; they are:

1. Lagrange Calcilutite Member
2. Crab Creek Calcilutite Member
3. Djugun Member

A summary of these units in terms of lithological descriptions, extant and former depositional lithotopes, and former environment of deposition is provided in Table 5. Detailed formal descriptions of the new stratigraphic units are provided in the next section.

The Christine Point Clay was originally defined in King Sound by Semeniuk (1980), but the grey clay mangrove-bearing unit occurring in the northernmost part of the Canning Coast is lithologically similar. Consequently, in the northern Canning Coastal region at

Beagle Bay, the unit of structureless, bioturbated, to root-structured grey clay (terrigenous clay, mainly as kaolinite), with *in situ* and fallen stumps of mangroves (trunks of *Avicennia marina*, with embedded "shipworm", lower trunks and prop roots of *Rhizophora stylosa*, and lower trunks and buttress roots of *Ceriops tagal*) is referred to this Formation. Within the Formation at Beagle Bay, locally shells of *Pitar*, *Saccostrea cucullata*, *Ellobium aurisjudae* and *Cassidula angulifera* are preserved. Also, similar to the Christine Point Clay in King Sound, there are scattered carbonate nodules, locally with embedded fossils of the mud lobster *Thalassina anomala*, and various species of the fiddler crab *Uca*.

The rationale for nomenclature of the new stratigraphic units is discussed below.

Following recommended practice by the International and the Australian Stratigraphic Code of Nomenclature (Hedberg 1976; Staines 1985; Salvador 1994; Lenz *et al.* 1996; Murphy & Salvador 1999), the geographic name that comprises the first part of the binomial of a given Formation described in this paper has been selected to be the formal geographic name (as noted on 1:250,000 and 1:100,000 topographic maps) where the type section or type location occurs, or a geographic name in relatively close proximity to the site of the type section. Being Holocene stratigraphic units, often the best way to portray the characteristics of a given Formation is to provide also a type location for the depositional regime which represents its main lithotope (in other words, the "type lithotope"). So if a geographic name was not available (having been previously used in the literature), the geographic location where the Formation is well developed, or best developed as a lithotope was used. Often the type location (or the type lithotope where a Formation is best developed) and the type section are the same.

With regards to the lithological part of the binomial, the term "calcarenite" was applied if the Formation was wholly calcarenitic, *i.e.*, composed wholly/dominantly of sand-sized calcareous grains. Hence, Horsewater Soak Calcarenite and Willie Creek Calcarenite convey the lithological content of those Formations. Sandwiched between these two Formations is a calcareous unit composed of interlayered calcarenite, carbonate-intraclast breccia and conglomerate, coquina, and *in situ* beachrock. The term "calcarenite" does not convey the range of its lithologic content, and hence "limestone" is used to convey that it is calcareous, *i.e.*, Kennedys Cottage Limestone. Similarly, the suffixes "coquina" and "sand" convey the content of their respective Formations. The Barn Hill unit and Cape Gourdon unit are partly red quartz sand with calcarenite lenses and laminae – the suffixes "sand", "limestone", and "calcarenite" do not convey the lithological character of the unit and so "Formation" is used.

Facies changes within the Cable Beach Sand presented a particular set of problems in definition of the Formation, and in assigning some of the lithologic variation as suites to member status. In a beach environment, with the diverse contribution of sand grain types, shells, intraclasts, lithoclasts, the variable synsedimentary diagenesis (*e.g.*, beachrock development), and differential sedimentary response to waves, tides, winds and storms generating sand-dominated facies, shelly sand facies, interlayered sand-and-shell facies, and pebbly sand facies, the Cable Beach Sand itself along the length of the Canning Coast is lithologically variable. While its unifying features, to be recognised as a Formation, are the suite of interlayered lithologies and its sedimentary structures, and its dominantly sand facies, it can be indurated sufficiently to develop quite thick and laterally extensive beachrock. In this instance, the suite of sedimentary structures (lithological layering, lamination, bubble sand), grain composition, range of grainsizes, and shell content (shell beds, shell laminae) within the beachrock is similar to that in the beach sand (the former merely being a tidal-zone cemented version of the latter). The change of lithology from sand to rock (sand to calcarenite) is profound enough to warrant recognition of the indurated component as the Cape Boileau Calcarenite Member within the Formation. Similarly, with the break-up and reworking of beachrock ribbons of the Cape Boileau Calcarenite Member into calcarenite-intraclast pebbles, cobbles, boulders and slabs, the Cable Beach Sand varies from being conglomerate-depauperate to conglomerate-dominated to being wholly conglomeratic. The conglomerate-dominated and wholly conglomeratic portions of the Cable Beach Sand are formally recognised as the Lombadina Conglomerate Member). The concept of the Cable Beach Sand Formation and the members within is also shown in Figure 8. An illustration further showing the relation of the primary lithology of the Cable Beach Sand, its synsedimentary diagenetic derivative, the Cape Boileau Calcarenite Member, and its intraclastic reworked derivative, the Lombadina Conglomerate Member, also is shown in Figure 8.

The Sandfire Calcilutite as a Formation provided another particular set of problems in definition and nomenclature, in assessing whether to assign it to one Formation or three Formations. It exhibits vertical and lateral variability in colour, organic matter content, iron sulphide content, sedimentary structures, shell content, fossil mangrove tree/shrub content, lithification, expression of its diagenetic history, and fundamental alteration of the lithology because of diagenesis. In the modern environment, there are three depositional lithotopes that involve calcilutaceous sediment (*viz.*, the zone of mixing between Pleistocene red sand and Holocene tidal flat calcilutite; the laminated and shelly deposits that underlie the mid- to low-tidal flats; and mangrove- and samphire-inhabited mid- to high tidal muddy flats), and they can generate three separate lithological units which could be considered to be three separate Formations.

There is a ubiquitous muddy sand in the region that is interposed between the Pleistocene red sand of the hinterland and the main bodies of Holocene tidal flat calcilutite. Depending on the slope of red sand terrain at this interface, and the extent that kaolinite is reworked from the red sand terrain into the tidal flat by sheet wash or run-off, the mud component of the muddy sand varies from carbonate-dominated to a mixture of carbonate and kaolinite, and the thickness of this muddy sand varies from < 30 cm to *circa* 2 m. It is a regionally mappable though relatively thin unit in comparison to the bulk of the Formation, and merely represents the (consistently present) transition zone between red sand and calcilutite,

Table 4

Main modern lithosomes and their sedimentary environments

Lithosome	Description of sediment	Modern sedimentary environment, origin of sediment and development of sedimentary features
structureless to large-scale cross-bedded and cross-laminated red quartz sand	mainly structureless to locally cross-laminated and cross-bedded medium and fine-grained quartz sand; the quartz has a red coating of iron oxides and dust	formed in coastal and near-coastal environments by modern aeolian reworking of the Pleistocene Mowanjum Sand to form coastal red dunes; the mobile dunes are cross-bedded and cross-laminated whereas older dunes, bioturbated by plants and fauna, or dunes that have migrated into scrub, shrubland, and heath are structureless
interlaminated and interbedded quartz carbonate sand (to calcarenite) and red quartz sand	interlaminated and interbedded carbonate-rich sand, quartz-and-carbonate sand, and quartz sand; laminae of the various sand types may be a few sand grains thick varying up to millimetres thick, or form beds up to several centimetres thick; the sand is medium and fine-grained, with local laminae of coarse sand; carbonate-dominated layers, whether sand or calcarenite, are composed of quartz, bioclasts, and ooids; calcarenites are cemented by fine-grained sparry calcite; quartz-dominated layers are medium and fine-grained quartz sand; the quartz has a red coating of iron oxides and dust	formed in coastal and near-coastal environments by modern aeolian reworking of the Pleistocene Mowanjum Sand and onshore aeolian delivery of carbonate-rich sand or white quartz sand as white coastal dunes; with land-breeze and sea-breeze processes, the red sand and the coastally derived white sands interdigitate and are mixed as alternating laminae and beds; the cross-bedding and cross-lamination have developed by migrating dunes and by incremental burial of the undulating dune topography; through early diagenesis, meteoric waters have transformed the ooid rich layers into calcarenite (*cf.* Logan 1974, who described similar rapid lithification of oolitic sand to weakly cemented calcarenite)
large-scale cross-bedded and cross-laminated white sand	large-scale cross-bedded and cross-laminated fine to medium white sand; sand is comprised of quartz, bioclasts, intraclasts, lithoclasts, and ooids; locally, there are shell grit laminae and shell laminae	formed in coastal environments as white shore-parallel coastal dunes by modern aeolian delivery of fine and medium sand and during strong winds and storms of coarse sand, shell grit and small shells; the cross-bedding and cross-lamination have developed by migrating dunes and by incremental burial of the undulating dune topography; aeolian removal of sand, or migration of dunes, leaving wind lags, have developed laminae of shell grit and shells
cream to buff or tan, small-scale cross-laminated to laminated sand and shelly sand	laminated and bedded medium, and low angle cross-laminated coarse to fine sand, shelly sand, and some beds or laminae of shell grit	formed along high energy beach zones as beach sand and shelly beach sand; the sand is derived by erosion of Mowanjum sand, from reworking of coastal dune sand, by fragmentation of resident benthos and local rocks, by delivery by longshore drift from alongshore sources, and from offshore sand sources such as invertebrate benthos, foraminifera, and ooids; wave reworking has rounded the grains and removed the red coatings from the red sand grains; local benthos have contributed shells, and produced vertical burrows; wave action and tidal currents have partitioned the grainsizes and generated the lamination and cross-lamination
sand and shelly sand with bubble structure	laminated and bedded, and low angle cross-laminated medium, coarse to fine sand and shelly sand, with layers of bubble structures; bubble structures are rounded to amoeboid cavities one to several millimetres in size; sand is quartz, bioclasts, intraclasts, lithoclasts, and ooids	formed in the upper beach zone; with a rising tide, beach sediment (as described above), subject to a rising water table, coupled with upper swash zone wave run-up and infiltration, develops a bubble structure in the upper parts of the beach slope (*cf.* Reineck & Singh 1980; Semeniuk 1997)
beachrock	calcarenite and shelly calcarenite comprised of laminated and bedded medium, coarse to fine sand and shelly sand, with layers of bubble structures, and vertical burrows; interstitially cemented by aragonite or Mg-calcite	formed in the upper beach zone; beach sediment (as described above) can become cemented in the mid-tidal to upper-tidal zone by aragonite and Mg-calcite; the beachrock is an indicator of mid-tidal to upper-tidal zone conditions

Table 4 (cont.)

Lithosome	Description of sediment	Modern sedimentary environment, origin of sediment and development of sedimentary features
limestone-intraclast conglomerate and breccia	aggregation of rounded to angular boulders, cobbles to pebbles of calcarenite and shelly calcarenite intraclasts free of matrix or embedded in sand	formed in the upper beach zone and at storm levels (supratidal zone); storms, especially cyclones, undercut, erode, and rework beachrock into slabs and other fragments and transports them upslope into the storm surge zone, forming a boulder, cobble, and pebble deposit (*cf.* Semeniuk 1996 who described similar deposits in the Pilbara Coast); they may remain matrix free, but later aeolian influx may partially bury such deposits
grey bioturbated sand and shelly sand	homogeneous, to bioturbated, to locally laminated and cross-laminated mainly medium grey sand, but locally fine and coarse sand with shell; the grey character is due to disseminated pyrite	formed in low-tidal environments; sand is quartz, and bioclasts and foraminifera; resident benthos contribute shells and bioturbate the sediment; tidal current and wave reworking of the surface in local areas generates cross-laminated and laminated brown (oxidised) sand; wave reworking also develops shell lags on the surface or shelly sand layers
monomictic shell gravel (monomictic coquina)	gravel-sized accumulation of shells, composed mainly of one mollusc species; usually composed of whole *Anadara* or *Modiolus*, or of fragmented *Saccostrea cucullata*, usually < 10 cm thick, though for *Anadara* up to 1 m thick	formed in cheniers as a storm deposit concentrated from mangrove environments (shell gravel of fragmented *Saccostrea*); *Anadara* or *Modiolus* monomictic shell gravel formed on tops of cheniers, or on supratidal dunes as Indigenous people harvested *Anadara* or *Modiolus* for food, leaving shells as middens
oligomictic shell gravel (oligomictic coquina)	gravel-sized accumulation of shells composed mainly of several mollusc species, e.g., *Sepia-Spirula* assemblages, or mixed *Anadara* and *Saccostrea cucullata*	*Sepia-Spirula* assemblages formed at highwater mark or at storm levels as a gravel; these shells float, and are brought in on the high water; later the shells may be buried by aeolian sand; mixed *Anadara* and *Saccostrea cucullata* shell gravel formed on tops of cheniers, or on supratidal dunes as Indigenous people harvested these species for food leaving shells as middens
polymictic shell gravel (polymictic coquina)	gravel-sized accumulation of shells composed of many species of mollusc	formed in many environments (*viz.*, shell gravel beds, cheniers, beach faces, or along the eroding front of a coast); in their most simple form, these deposits have formed within a lithotope by wave action or storm action concentrating shells by winnowing; alternatively, they can form as a result of transport from a number of environments (the accumulations of shell deposits from a range of biotopes and lithotopes); addition of shell material as middens adds to the heterogeneity
root-structured, shelly calcilutite, grading into bioturbated calcilutite, grading to structureless calcilutite	grey to grey/cream carbonate mud, with bioturbation structures, *in situ* mangrove trunks, fallen mangrove branches, wood fragments, and scattered shells; the shells range from entire tests to fragments	formed under mangrove cover: carbonate mud accumulates under processes of scour lag / settling lag (Postma 1961); mangrove trunk stumps buried *in situ*, or fallen trunks, branches and wood fragments, accumulate in the mud; resident shells on trunks or on substrate contribute to shell content of sediment; biogenic structures include root-structuring by mangroves, and burrowing by crustaceans, fish, worms and molluscs; leaf litter contributes organic matter to the sediment which, through microbial decay, develops fine-grained pyrite which imparts a grey tone to the sediment; later oxidation of organic matter and pyrite, and dissolution of shell results in a cream bioturbated calcilutite to structureless calcilutite
laminated shelly calcilutite	grey/cream to cream carbonate mud, laminated to sparsely burrow-structured to alternating beds of laminated mud and structureless mud, with scattered to abundant shells; some beds are shell-dominated; the shells in the sediment range from entire shells to fragments	formed in mid-tidal to low-tidal zones; carbonate mud accumulates under processes of scour lag / settling lag (Postma 1961), forming laminated sediment; resident molluscs contribute shells to the sediment; burrowing organisms, especially crabs and fish generated laminae-transgressive burrows (burrow structured sediment); burrowing by crustaceans, fish, worms and molluscs develops bioturbation structures; storm and wave activity develops shell lag concentrates; bioturbation generates shell fragments especially the thin shelled tellinids which are common in the sediment
bioturbated shelly calcilutite	bioturbated to structureless grey/ cream to cream carbonate mud, with scattered to abundant shells; some horizons are shell-dominated; the shells in the sediment range from entire shells to fragments	formed in mid-tidal to low-tidal zones; carbonate mud accumulates under processes of scour lag / settling lag (Postma 1961); abundance of burrowing organisms develops bioturbation structures; storm and wave activity develops shell lag concentrates; bioturbation results in shell fragmentation, especially the thin-shelled tellinids which are common in the sediment

Table 5

Summary of lithological characteristics of the new stratigraphic units and their depositional environment

Formation	Generalised lithological description and depositional environment
Shoonta Hill Sand	white fine-grained sand; shoe-string to lensoid deposit formed as supratidal dunes
Eighty Mile Beach Coquina	shell gravel; ribbon deposit mainly formed under a winnowed beach face
Cable Beach Sand	laminated, bedded, to low-angle cross-bedded, medium to fine to coarse sand and shelly sand; locally, patches of mid- to high tidal cemented *in situ* beach rock, and slabs and breccia (the latter two embedded in laminated sand), bubble sand, and cross-laminated shelly sand and sand; when prograded it forms a sheet deposit under tidal beach face, otherwise it is ribbon-shaped in geometry
Cape Boileau Calcarenite Member	cemented beachrock composed of laminated, bedded, to low-angle cross-bedded, medium to fine to coarse calcarenite and shelly calcarenite, with local layers of bubble sand, and locally incorporated slabs and breccia of (earlier cemented beachrock) intraclasts; ribbon deposit formed on and buried under the tidal beach face
Lombadina Conglomerate Member	within the Cable Beach Sand, deposits of reworked beachrock forming rounded slabs and breccia, pebble to boulder sized; these fragments of beach rock are embedded in laminated sand, bubble sand, and cross-laminated shelly sand and sand, or form a sand-free deposit resting on beachrock pavement; ribbon deposit formed along upper tidal beach face
Port Smith Sand	grey to brown/tan/buff, bioturbated to laminated sand and shelly sand; ribbon deposit formed under low sandy tidal flats
Race Course Plains Coquina	shell gravel; formed in shoe-string, to lensoid, to wedge-shaped deposits as chenier ridges, shoreline spits, and shoreline shell beds
Sandfire Calcilutite	white/cream/grey largely structureless, to bioturbated, to laminated, to locally indurated calcilutite; grades into underlying sand *via* calcilutaceous muddy sand, and into laterally adjoining sand *via* kaolinitic and calcilutaceous muddy sand; underlies salt flats, samphire flats, mangrove flats, and mid low tidal flats; prism to wedge-shaped deposit formed under muddy tidal flats (note that this Formational description encompasses the lithological characteristics of its component three members)
Lagrange Calcilutite Member	within the Sandfire Calcilutite, those deposits which are white/cream/grey bioturbated (locally laminated) calcilutite; underlies salt flats, samphire flats, and mangrove flats
Crab Creek Calcilutite Member	within the Sandfire Calcilutite, those deposits which are white/cream shelly, laminated to burrow-structured calcilutite; underlies mid-low tidal flats
Djugun Member	within the Sandfire Calcilutite, the deposits which are muddy red quartz sand, muddy brown quartz sand (mud in the muddy sand is kaolinitic and/or calcilutaceous); sheet-like deposit occurring between red sand and calcilutite
Cape Gourdon Formation	bedded and laminated to cross-laminated interlayered red, orange and white quartz and quartz-and-carbonate sand, and locally gravelly sand, with small limestone lenses; discontinuous lensoid deposit formed as supratidal shoreline alluvial fans and dunes
Barn Hill Formation	structureless to laminated to cross-laminated red quartz and quartz-and-carbonate sand, with large to small limestone lenses, limestone beds, and carbonate-rich sand laminae; carbonate content is bioclastic, carbonate-intraclast, carbonate-lithoclast, and oolitic; shoe-string to lensoid deposit formed as supratidal dunes
Church Hill Sand	mainly structureless, but locally laminated to cross-laminated red quartz sand; shoe-string to lensoid deposit formed as supratidal dunes
Horsewater Soak Calcarenite	cross-laminated aeolian calcarenite; shoe-string deposit formed as earlier Holocene supratidal dunes
Kennedys Cottage Limestone	cross-laminated (beach) shelly calcarenite and calcarenite, with bubble sand layers, *in situ* beachrock, and conglomerate and breccia of carbonate intraclasts; ribbon deposit formed as an earlier Holocene beach sediment
Willie Creek Calcarenite	bedded to large-scale festoon-bedded, laminated, burrow-structured to bioturbated calcarenite and shelly calcarenite; ribbon deposit formed as an earlier Holocene mid- to low-tidal sand and shelly sand
Christine Point Clay (after Semeniuk 1980)	structureless, bioturbated, to root-structured grey clay composed of terrigenous clay, with mangrove stumps

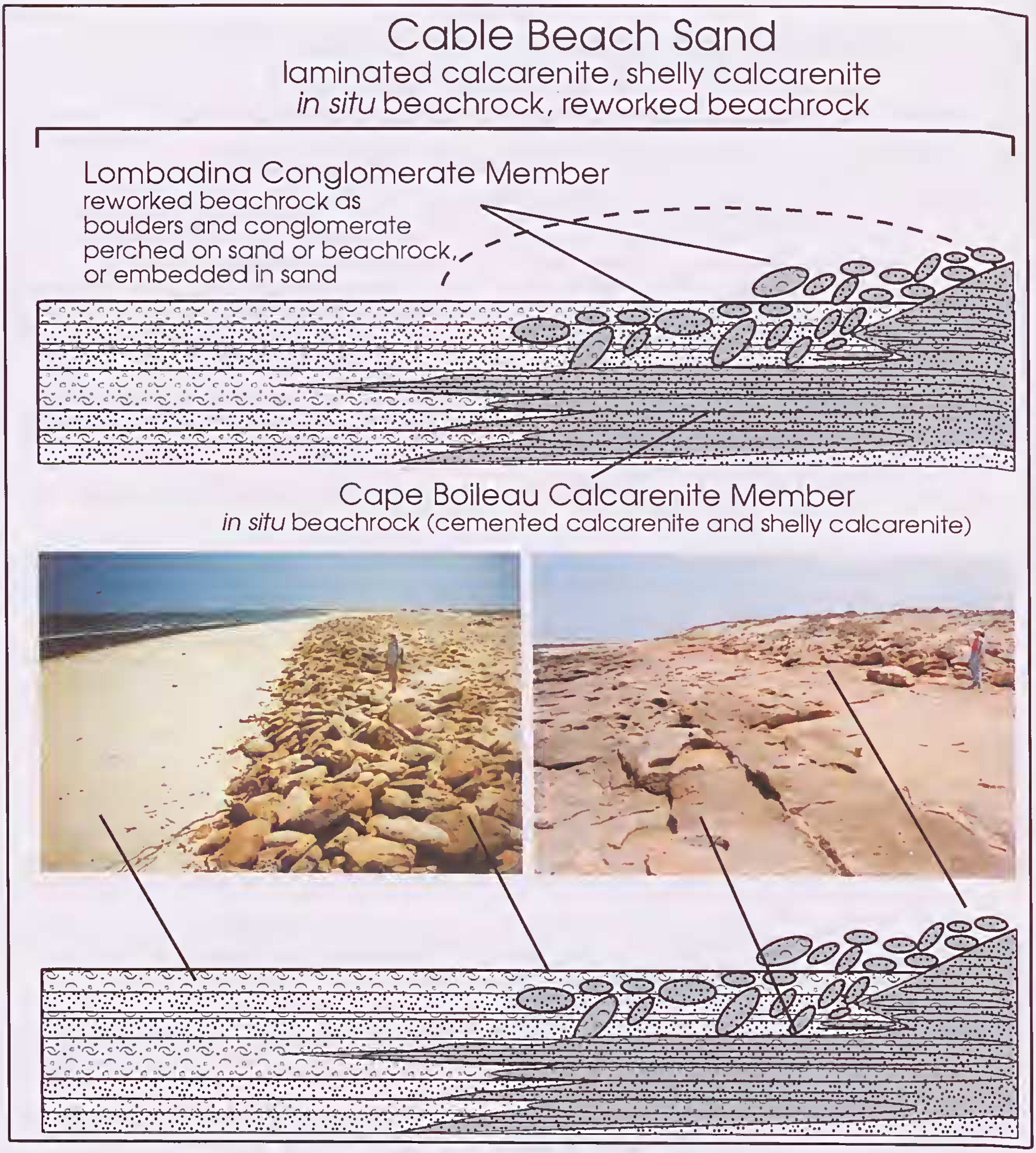


Figure 8. The concept of Cable Beach Sand as a formation and its component members (the Cape Boileau Calcarenite Member and the Lombadina Conglomerate Member) where beachrock and reworked beachrock forming boulder deposit are developed.

albeit the thickness locally can be 2 m. Its consistent stratigraphic location and its occurrence as a transitional unit between two Formations suggest it should be afforded some formal recognition, but only to member status, *i.e.*, the Djugun Member, not to Formational status.

The mid-low tidal flats, with their resident benthos, are underlain by laminated calcilutite with whole and fragmented shell and locally, absence of shell. However, bioturbation and further shell fragmentation (where there was shell, with some shell dissolution) can transform this lithological unit into a bioturbated to structureless (slightly shelly) cream-toned calcilutite. Its occurrence generally is restricted – it is best developed in the low-tidal areas of Roebuck Bay, and only locally in patches elsewhere. While it is distinct when it occurs as a laminated shelly unit, it grades through diagenesis into structureless calcilutite diagnostic of Sandfire Calcilutite, but it is not consistent enough to be afforded Formational status, and so is designated member status, *i.e.*, Crab Creek Calcilutite Member. The mid- to high tidal flats are inhabited by mangroves and samphire. Sediment initially accumulates under mangrove cover as grey carbonate mud, with disseminated organic matter, mangrove trunks, branches and wood fragments, and various shells (such as *Cerithidea cingulata*, *Cerithidea obtusa*, *Nerita undata*, *Pitar* sp., *Saccostrea cucullata*, *Terebralia palustris*, *Telescopium telescopium*, and shipworm Teredinidae). The sediment is bioturbated to root-structured, and locally vaguely laminated. The sediment is diagenetically transformed in time to lighter grey to cream in tone, and with decay of mangrove matter and dissolution of the shells, the mangrove-diagnostic sediment becomes cream, sparsely shelly, bioturbated to structureless calcilutite. The transformation of the sediment with a strong signature of the mangrove environment into a structureless to bioturbated calcilutite is a diagenetic one, and although it is a general pattern regionally, it is not consistent and it means that lithologically distinct sediment in time diagenetically alters to less environmentally diagnostic calcilutite. In this context, all the calcilutite is referred to the Sandfire Calcilutite at Formation level, and if calcilutite still carries the signature of the mangrove environment lithotope, it is referred to a particular member, *i.e.*, the Lagrange Calcilutite Member within the Formation.

As such, the Sandfire Calcilutite carries the definition of being calcilutite, but it has lithological variation from structureless and bioturbated cream calcilutite (the dominant characteristic of the Formation) to sediment suites that can be referred to the Djugun Member (a stratigraphically long term and lithologically permanent component at the base of the Formation), the Lagrange Calcilutite Member (a mid- to upper-tidal depositional phase of the Formation), and Crab Creek Calcilutite Member (a mid- to lower tidal depositional phase of the Formation, or a local facies variant of the Formation). Older parts of the Formation that occur along the stranded middle Holocene shoreline tend to be consistently more indurated. A diagrammatic illustration of the range of primary lithology, synsedimentary diagenetic effects, and later diagenetic effects in developing the variety of lithology in the Sandfire Calcilutite is shown in Figure 9.

Type sections, supplementary sections, and various cross sections showing stratigraphic relationships, and the relationships of the stratigraphic units to the coastal settings are illustrated in Figures 10–31. A summary of the stratigraphic relationships is shown in Figure 32.

While the illustrations presented later show the areal extent of some of these Formations, it is to be stressed that these are maps of stratigraphic units, not geomorphic units. The stratigraphic units have been differentiated on lithologic criteria. However, in many situations, the Formations tend to have a specific geomorphic setting, e.g., Cable Beach Sand underlies the shore-parallel beach unit, the Sandfire Calcilutite underlies mangrove vegetated mid-high tidal mud flats, the Horsewater Soak Calcarenite underlies the limestone barriers that bar many of the embayments, and the Race Course Plains Coquina underlies the high-tidal chenier systems. The correlation is so direct in these Holocene coastal settings, that mapping the geomorphic units often effectively maps the stratigraphic units, but this is not always the case, For instance, shore-parallel ridges of calcarenite of Pleistocene age are difficult to separate from those of Holocene age; similarly, cheniers can superficially geomorphically resemble calcarenite ridges.

Definition of the new stratigraphic units

Shoonta Hill Sand

Definition and characteristics:

The Shoonta Hill Sand is the name proposed for the light-coloured to white, fine (to medium) calcareous dune sand that occurs along the Canning Coast.

Derivation of Name:

Shoonta Hill area, a region of well developed coastal sand dunes, latitude/longitude coordinates 19° 55' 51" S, 120° 10' 43" E, Mandora 1:250,000 Topographical Sheet.

Type section (Type locality):

Shoonta Hill, latitude/longitude coordinates 19° 55' 02" S, 120° 11' 20" E, Mandora 1:250,000 Topographical Sheet.

Distribution:

The unit is widespread as a shoe-string to lensoid deposit along the Canning Coast.

Thickness and geometry:

Where intersected in cores and trenches, the Formation has been recorded as up to 8 m thick. Regionally, the unit will appear as a continuous to locally discontinuous shoe-string to lensoid deposit of variable thickness and width, some tens to hundreds of kilometres long, but only up to 500 m wide and up to 8 m thick.

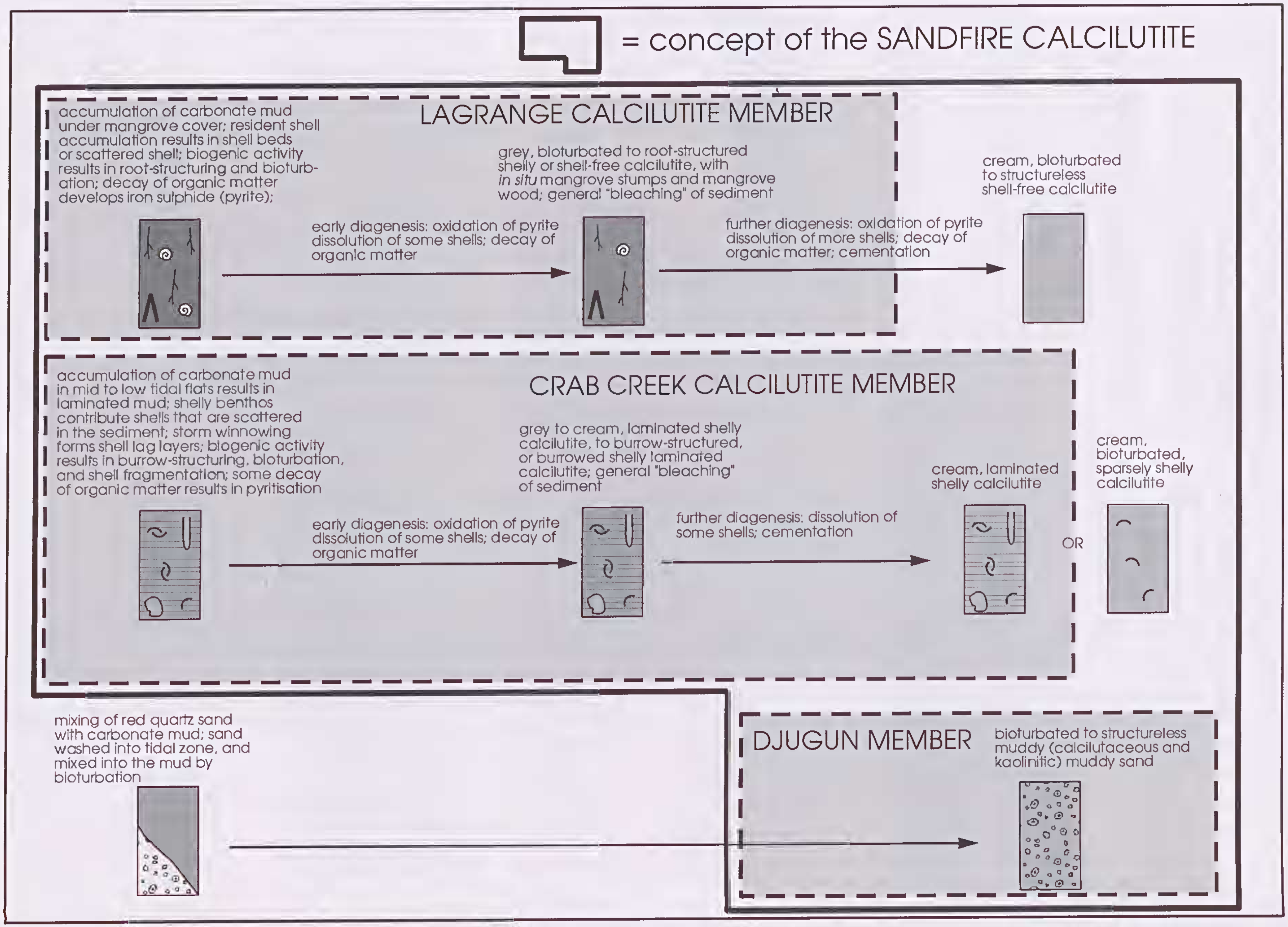
Lithology:

In general, light-coloured to white, laminated, cross-laminated to bedded, to structureless and root-structured quartzose calcareous fine to medium sand. Calcareous sand grains are bioclasts, foraminifera, intraclasts, some lithoclasts, and locally ooids (Figures 7H, 7L and 7 N). The type section intersected along the shore face at Shoonta Hill (Figure 28) consists of:

Description	Thickness
cream to light coloured fine/medium quartzose and calcareous sand large-scale cross-bedding and cross-lamination, with local shell horizons	8 m

The top of this section is the modern dune surface. The base of the unit commonly is located at HAT.

Shell horizons have developed in the Formation as wind lag deposits in the bowls of deflation hollows or deflation flats. These shell horizons are dominated by *Donax faba*, *Paphies* sp, and *Sepia* spp, or their fragments. In the Camp Inlet area, the Formation is expressed as a large coastal erg wherein there are many local (surface) wind lag deposits, and wind exposed


= concept of the SANDFIRE CALCILUTITE
LAGRANGE CALCILUTITE MEMBER
accumulation of carbonate mud under mangrove cover; resident shell accumulation results in shell beds or scattered shell; biogenic activity results in root-structuring and bioturb-ation; decay of organic matter develops iron sulphide (pyrite);
early diagenesis: oxidation of pyrite dissolution of some shells; decay of organic matter
grey, bioturbated to root-structured shelly or shell-free calcilutite, with in situ mangrove stumps and mangrove wood; general "bleaching" of sediment
further diagenesis: oxidation of pyrite dissolution of more shells; decay of organic matter; cementation
cream, bioturbated to structureless shell-free calcilutite
CRAB CREEK CALCILUTITE MEMBER
accumulation of carbonate mud in mid to low tidal flats results in laminated mud; shelly benthos contribute shells that are scattered in the sediment; storm winnowing forms shell lag layers; biogenic activity results in burrow-structuring, bioturbation, and shell fragmentation; some decay of organic matter results in pyritisation
early diagenesis: oxidation of pyrite dissolution of some shells; decay of organic matter
grey to cream, laminated shelly calcilutite, to burrow-structured, or burrowed shelly laminated calcilutite; general "bleaching" of sediment
further diagenesis: dissolution of some shells; cementation
cream, laminated shelly calcilutite
OR
cream, bioturbated, sparsely shelly calcilutite
mixing of red quartz sand with carbonate mud; sand washed into tidal zone, and mixed into the mud by bioturbation
DJUGUN MEMBER
bioturbated to structureless muddy (calcilutaceous and kaolinitic) muddy sand

middens composed of polymictic thanatocoenoses (with *Melo amphora*, *Saccostrea cucullata*, *Telescopium telescopium*, *Terebralia palustris*, and *Anadara granosa*) brought to the area by Indigenous people earlier in the Holocene.

Various supplementary sections drawn from the Camp Inlet area, Cable Beach area, Barn Hill area, Mandora area, and Cape Keraudren area are illustrated in Figures 11, 13, 16–17, 25–27, and 29. At Mandora Station on the coast it is 6 m thick.

Locally, where the sands have been stabilised in the past, there has been development of humic soils which now are buried paleosols (Figure 11).

Stratigraphic relationships:
The unit passes downwards, with gradational contact into Cable Beach Sand. Depending on setting, it overlies with sharp contact the Mowanjum Sand, or Church Hill Sand, or Barn Hill Formation, or Eighty Mile Beach Coquina. Locally, the unit sharply overlies the Sandfire Calcilutite (Figures 25–27).

Fauna:
Mollusc shells occur in the lower part of the Formation, near its contact with Eighty Mile Beach Coquina and Cable Beach Sand, also in horizons within the Formation, representing wind lag deposits (include *Donax faba* and *Sepia* spp), and as midden deposits.

Age:
Radiocarbon dating of shells and soil within the Formation places it in the Holocene, *viz.*, 1190 ± 170 yrs BP, 2440 ± 190 yrs BP (Table 6, and Figures 11 and 16).

Discussion:
The Shoonta Hill Sand is a distinctive and widespread white fine to medium sand unit formed in coastal dune environments.

Eighty Mile Beach Coquina

Definition and characteristics:
The Eighty Mile Beach Coquina is the name proposed for light-coloured, laminated, cross-laminated to bedded, shell gravel and shelly sand occurring along the Canning Coast.

Derivation of Name:
Eighty Mile Beach, latitude/longitude coordinates 19° 40' 53" S, 120° 49' 44" E, Mandora 1:250,000 Topographical Sheet.

Type section (Type locality):
Coastal zone north east of Mandora homestead, latitude/longitude coordinates 19° 40' 31" S, 120° 51' 26" E, Mandora 1:250,000 Topographical Sheet.

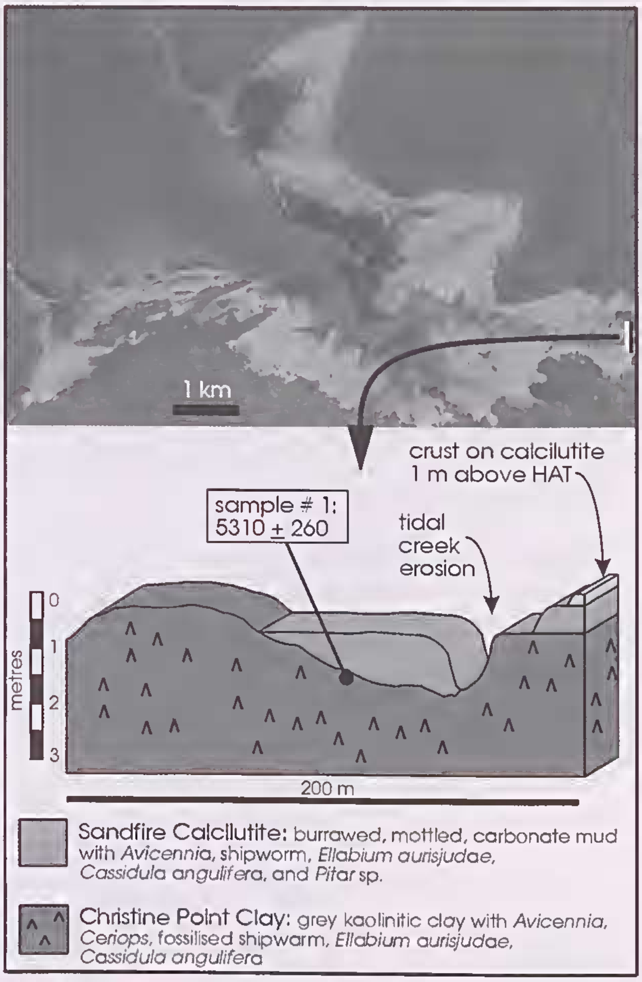
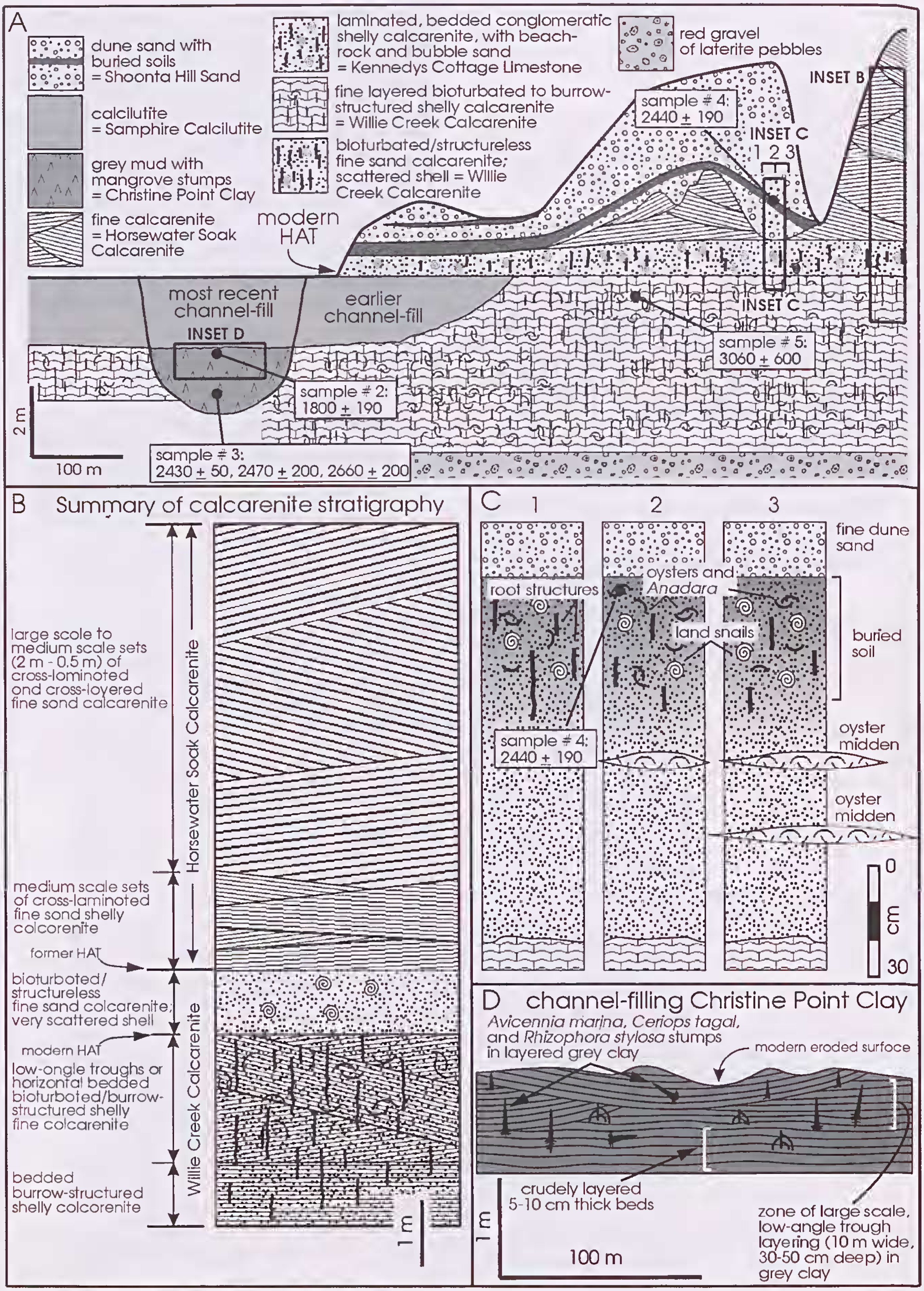


Figure 10. Stratigraphic profile at the eastern head of Beagle Bay, showing Sandfire Calcilutite overlying a erosional channel cut into Christine Point Clay.

Distribution:
The unit is widespread though discontinuous along the Canning Coast.

Thickness and geometry:
In sections where coasts are retreating, the Eighty Mile Beach Coquina tends to be a 30–50 cm thick veneer on the beach face. In sections that are progradational, the Formation is developed as a ribbon 1–2 m thick. It commonly sits perched on a buried erosional cliff at depth representing periods of coastal retreat, where seacliffs or steep slopes cut into calcilutite or beach sand have been buried in the Holocene stratigraphic record. Where intersected in cores and trenches, the Formation has been recorded as 3 m thick. Regionally, the unit will appear as a discontinuous ribbon, some tens of

◀ Figure 9. The concept of Sandfire Calcilutite as a formation and its component members (the Lagrange Calcilutite Member, the Crab Creek Calcilutite Member, and the Djugun Member) and the sedimentary processes, synsedimentary diagenetic processes, and early diagenetic processes that lead to the development of the various lithologies within the formation. Symbols within the lithology denote mangrove stumps, ramifying and bifurcating root structures, gastropods, bivalves, and burrow mottles.


A
dune sand with buried soils = Shoonta Hill Sand
calcilutite = Samphire Calcilutite
grey mud with mangrove stumps = Christine Point Clay
fine calcarenite = Horsewater Soak Calcarenite
laminated, bedded conglomeratic shelly calcarenite, with beach-rock and bubble sand = Kennedys Cottage Limestone
fine layered bioturbated to burrow-structured shelly calcarenite = Willie Creek Calcarenite
bioturbated/structureless fine sand calcarenite; scattered shell = Willie Creek Calcarenite
red gravel of laterite pebbles
modern HAT
INSET B
sample # 4: 2440 ± 190
INSET C
1 2 3
most recent channel-fill
earlier channel-fill
INSET D
INSET C
sample # 5: 3060 ± 600
sample # 2: 1800 ± 190
sample # 3: 2430 ± 50, 2470 ± 200, 2660 ± 200
2 m
100 m
B Summary of calcarenite stratigraphy
large scale to medium scale sets (2 m - 0.5 m) of cross-laminated and cross-layered fine sand calcarenite
Horsewater Soak Calcarenite
medium scale sets of cross-laminated fine sand shelly calcarenite
former HAT
bioturbated/ structureless fine sand calcarenite; very scattered shell
modern HAT
low-angle troughs or horizontal bedded bioturbated/burrow-structured shelly fine calcarenite
Willie Creek Calcarenite
bedded burrow-structured shelly calcarenite
1 m
C 1 2 3
fine dune sand
root structures
oysters and Anadara
land snails
buried soil
sample # 4: 2440 ± 190
oyster midden
oyster midden
0
cm
30
D channel-filling Christine Point Clay
Avicennia marina, Ceriops tagal, and Rhizophora stylosa stumps in layered grey clay
modern eroded surface
crudely layered 5-10 cm thick beds
1 m
100 m
zone of large scale, low-angle trough layering (10 m wide, 30-50 cm deep) in grey clay

kilometres long, but only up to 100–200 m wide and up to 3 m thick.

Lithology:
Light-coloured, laminated, bedded to cross-laminated, polymictic shell gravel (Figure 7B), shell grit, shelly sand, and some coarse and medium sand layers. Sand grains are quartz, bioclasts and limestone intraclasts and lithoclasts. Lower parts of the Formation where sandy, have scattered vertical burrows of the sand bubbler crab *Scopimera*, and middle to upper parts have scattered vertical burrows of the ghost crab *Ocypode*.

The type section, along the shore face near Wallal Downs, consists of:

Description	Thickness
shelly sand with cuttlefish *Sepia* and crab burrows	50 cm
layered/laminated shell hash and sand	20 cm
sandy shell hash	10 cm
shelly sand	15 cm
sand with bubble structures	10 cm
shelly gravel	40 cm
shell gravel with sandy matrix	20 cm
shell gravel with shell grit matrix	10 cm

The top of the Formation at the type section is a sedimentary surface located at HAT.

Stratigraphic relationships:
The unit passes downwards, with sharp contact, into the underlying Port Smith Sand, and passes vertically upwards, with sharp contact, into the overlying Shoonta Hill Sand. Locally, the Formation has a sharp erosional contact with the laterally equivalent Sandfire Calcilutite (Figure 25). Figure 25 also shows a channel filled with Eighty Mile Beach Coquina cut into the Sandfire Calcilutite. The Eighty Mile Beach Coquina is also laterally equivalent to the Cable Beach Sand.

Fauna:
Molluscan shells in the Formation are polymictic thanatocoenoses, and include the most diverse of thanatocoenoses in the region, *viz.*, the bivalves *Acrosterigma reeveanum, Acrosterigma vlamingi, Anadara crebricostata, Anadara granosa, Antigona chemnitzii, Cardita incrassata, Chama reflexa, Chama* sp. 1, *Donax faba, Dosinia incisa, Eucrassatella pulchra, Hyotissa hyotis, Macoma praetexta, Mimachlamys scabricostata, Paphia semirugata, Paphies heterodon, Paphies striata, Pinna bicolor, Placamen gravescens, Placuna placenta, Saccostrea cucullata, Solen kajiyamai, Spondylus wrightianus, Tapes literatus, Tellina piratica, Trisidos semitorta, Trisidos tortuosa, Venus lamellaris, and* unidentified Pectinid, and an unidentified Venerid, and the gastropods *Bulla ampulla, Bulla guoyii, Chicoreus rubiginosus, Chicoreus ryosukei, Chicoreus* sp., *Cominella* cf. *lineolata, Conus textile, Conus trigonus, Cypraea pyriformis, Duplicaria duplicata, Ficus eospila, Fusinus colus, Herpetopoma atrata, Melo amphora, Murex macgillivrayi, Murex* cf. *acanthostephes, Nassarius dorsatus, Naticarius alapapiliones, Oliva lignaria, Planaxis sulcatus, Polinices conicus, Strombus campbelli, Terebralia palustris,* and an unidentified Trochid. It should be noted that most of the shell has been transported into the depositional lithotope from low tidal areas.

Age:
Radiocarbon dating of shells within the Formation places it in the Holocene, *viz.*, 3680 ± 210 yrs BP (Table 6, and Figure 26).

Discussion:
The Eighty Mile Beach Coquina is a distinctive, widespread polymictic shell gravel unit along high energy mid-high tidal beaches. On some coasts that are retreating, it may form a veneer in the beach zone.

Cable Beach Sand

Definition and characteristics:
The Cable Beach Sand is the name proposed for the light-coloured, laminated, bedded, to low-angle cross-bedded, medium to fine to coarse sand and shelly sand that occurs along the Canning Coast. Locally, there are patches of mid- to high tidal cemented *in situ* beach rock, and slabs and breccia, the latter embedded in laminated sand, bubble sand, and cross-laminated shelly sand and sand.

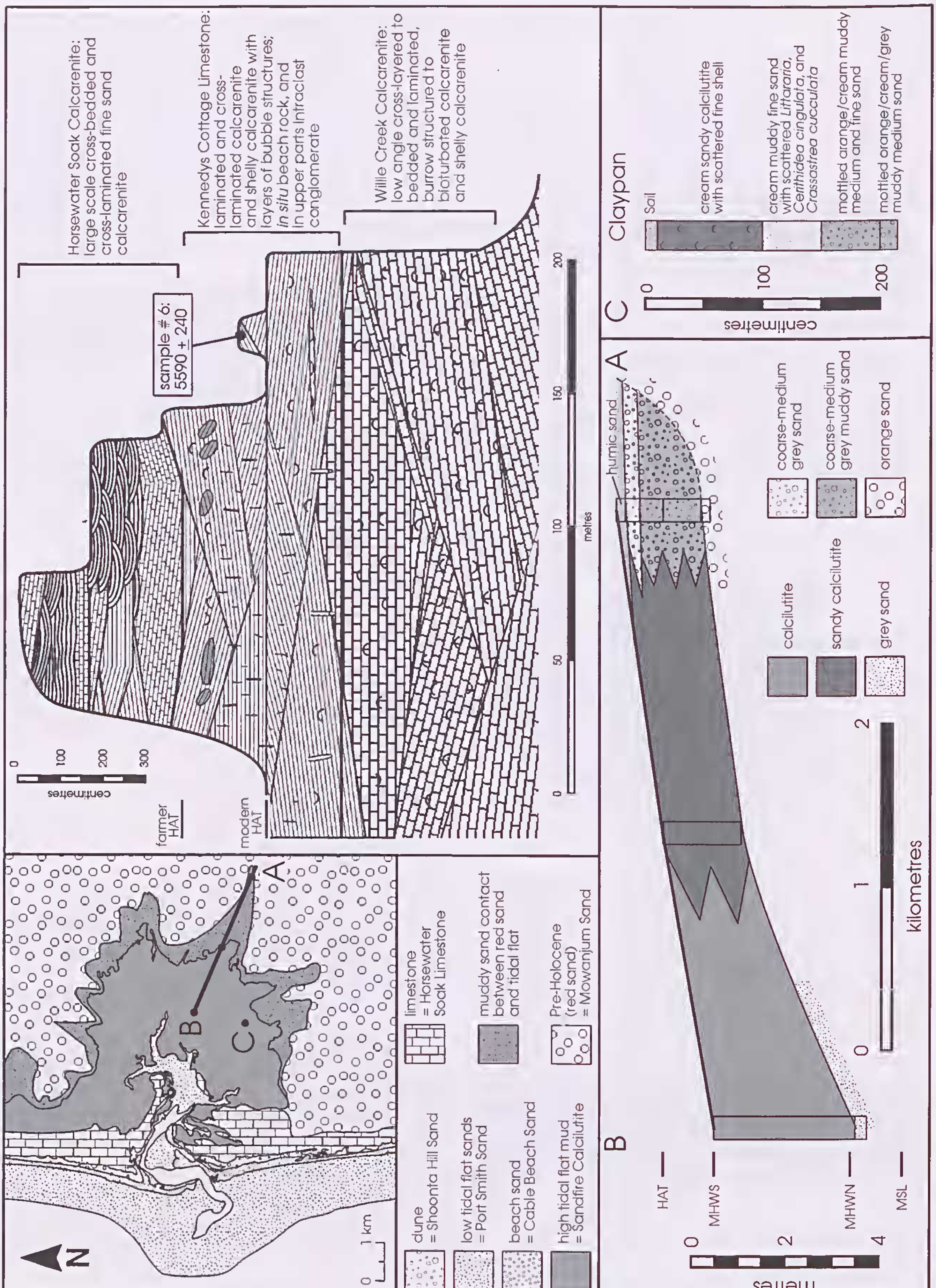
Derivation of Name:
Cable Beach, north of Broome, latitude/longitude coordinates 17° 54' 54" S, 122° 12' 41" E, Broome 1:250,000 Topographical Sheet.

Type locality:
Cable Beach, latitude/longitude coordinates 17° 54' 29" S, 122° 12' 50" E, Broome 1:250,000 Topographical Sheet.

Distribution:
The unit is widespread along the Canning Coast.

Thickness and geometry:
Along prograding coasts, the unit forms a sheet deposit, otherwise it forms a ribbon deposit under the beach face. Where coasts are retreating, the Cable Beach Sand tends to be a veneer 0.1–1 m thick on the beach

◀ **Figure 11.** Stratigraphic profile exposed as cliffs along the shore of western Camp Inlet. A. The Holocene calcarenite formations (Willie Creek Calcarenite, Horsewater Soak Calcarenite) overlie a gravel of laterite clasts. In turn, the Holocene calcarenite formations have been erosionally channelled, with the lower channel filled with grey mangrove-bearing clay (Christine Point Clay) and the upper channel with carbonate mud (Sandfire Calcilutite), and later eroded by wind action to yield mobile sand to develop sand dunes (Shoonta Hill Sand). B. The details of the stratigraphy of the Holocene calcarenite formations. C. Humic palaeosols (buried soils), and buried lenses of middens of oysters (*Saccostrea cucullata*). D. Diagram from cliff face showing large-scale sedimentary structures, layering, and *in situ* trunks and fallen trunks of *Avicennia marina* in the Christine Point Clay.


Horsewater Soak Calcarenite: large scale cross-bedded and cross-laminated fine sand calcarenite
Kennedys Cottage Limestone: laminated and cross-laminated calcarenite and shelly calcarenite with layers of bubble structures; in situ beach rock, and in upper parts intraclast conglomerate
Willie Creek Calcarenite: low angle cross-layered to bedded and laminated, burrow structured to bioturbated calcarenite and shelly calcarenite
sample # 6: 5590 ± 240
former HAT
modern HAT
centimetres
0
100
200
300
0
50
100
150
200
metres
N
0
1 km
A
B
C
dune = Shoonta Hill Sand
low tidal flat sands = Port Smith Sand
beach sand = Cable Beach Sand
high tidal flat mud = Sandfire Calcilutite
limestone = Horsewater Soak Limestone
muddy sand contact between red sand and tidal flat
Pre-Holocene (red sand) = Mowanjum Sand
metres
0
2
4
HAT
MHWS
MHWN
MSL
humic sand
kilometres
1
calcilutite
sandy calcilutite
grey sand
coarse-medium grey sand
coarse-medium grey muddy sand
orange sand
Claypan
Soil
cream sandy calcilutite with scattered fine shell
cream muddy fine sand with scattered Littoraria, Cerithidea cingulata, and Crassostrea cucculata
mottled orange/cream muddy medium and fine sand
mottled orange/cream/grey muddy medium sand

face. Where intersected in cores and trenches, the Formation has been recorded as 3 m thick. Regionally, the unit appears as a sheet to discontinuous ribbon, some tens of kilometres long, but only up to 100–200 m wide and up to 3 m thick.

Lithology:

Light-coloured, laminated, bedded, to low-angle cross-bedded, medium to fine to coarse sand and shelly sand and some shell gravel. Locally, the Formation is cemented to form beachrock which occurs as a sloping rock pavement. Sand grains may be dominantly quartz, or mixed quartz, bioclasts and limestone intraclasts and lithoclasts, and locally ooids (Figures 7I, 7J, 7K, 7M, and 7O). Shell content in the unit varies laterally, depending on the composition of the fauna that inhabited the contiguous low tidal flats. Locally, there are patches of mid- to high tidal cemented *in situ* beach rock forming shore-parallel ribbons, and indurated enough in some areas to form rock pavements. Where dominant, such cemented zones are referred to the Cape Boileau Calcarenite Member (Figure 8, and see below). Beachrock can be broken into slabs and reworked during storms, thus forming conglomerate and breccia beds in the upper-tidal zone (Figures 7A and 8); the slabs and breccia are embedded in laminated sand, bubble sand, and cross-laminated shelly sand and sand. Thus, ribbons of limestone-intraclast conglomerate and breccia are present locally in the Formation. Where dominant, such accumulations are referred to the Lombadina Conglomerate Member (Figure 8, and see below).

Because it is sandy, burrows and bubble sand are more evident here than in the laterally equivalent Eighty Mile Beach Coquina. Lower parts of the unit contain vertical burrows of *Scopimera*, the sand bubbler crab, and middle to upper parts have scattered vertical burrows of the ghost crab *Ocypode*. Bubble sand is locally preserved in upper parts of the unit. Uppermost parts of the Formation also contain storm debris, including cuttlefish *Sepia*, and *Spirula spirula*.

A partial section at the type locality at Cable Beach (core 5), consists of:

Description	Thickness
Shoonta Hill Sand	
shelly sand with *Sepia* and crab burrows	10 cm
layered/laminated medium sand	90 cm
laminated sand and shell gravel	100 cm
laminated coarse sand	60 cm
laminated medium sand	60 cm

The top of the section is the upper beach surface located at HAT.

Supplementary sections of the Cable Beach Sand are shown in Figures 13 and 28.

Stratigraphic relationships:

The unit passes downwards, with gradational contact, into the underlying Port Smith Sand, and passes vertically upwards, with gradational contact, into the overlying Shoonta Hill Sand. The Formation is laterally equivalent to the Eighty Mile Beach Coquina and to the Sandfire Calcilutite. Locally, it interfingers with, and is overlain by the Cape Gourdon Formation.

Fauna:

Autochthonous molluscan shells in middle to upper parts of the Formation include: *Donax faba*, *Paphies* sp., *Nassarius dorsatus* and *Oliva lignaria*. These are autochthonous biocoenoses. Transported molluscs shells (thanatocoenoses) include *Acrosterigma reeveanum*, *Anadara crebricostata*, *Anadara granosa*, *Cardita incrassata*, *Melo amphora*, *Mimachlamys scabricostata*, *Oliva lignaria*, *Pinna bicolor*, *Septifer bilocularis*, *Solen kajiyamai*, *Spondylus wrightianus* and *Trisidos tortuosa*. Where mixed with the local shells, they form mixed biocoenoses/thanatocoenoses. It should be noted that much of the shell has been transported into the depositional lithotope from low tidal areas. Where such transport has been dominant, the assemblage is an allochthonous thanatocoenosis. Shells in the upper part of the Formation include *Donax faba*, *Sepia* spp and *Spirula spirula*. Depending on whether cephalopod skeletons or *Donax faba* dominate, or are totally mixed, these are allochthonous biocoenoses, or allochthonous thanatocoenoses, or mixed biocoenoses/ thanatocoenoses.

Age:

Radiocarbon dating of shells within the Formation places it in the Holocene, *viz.*, 1090 ± 160 yrs BP and 2100 ± 180 yrs BP (Table 6, and Figure 13).

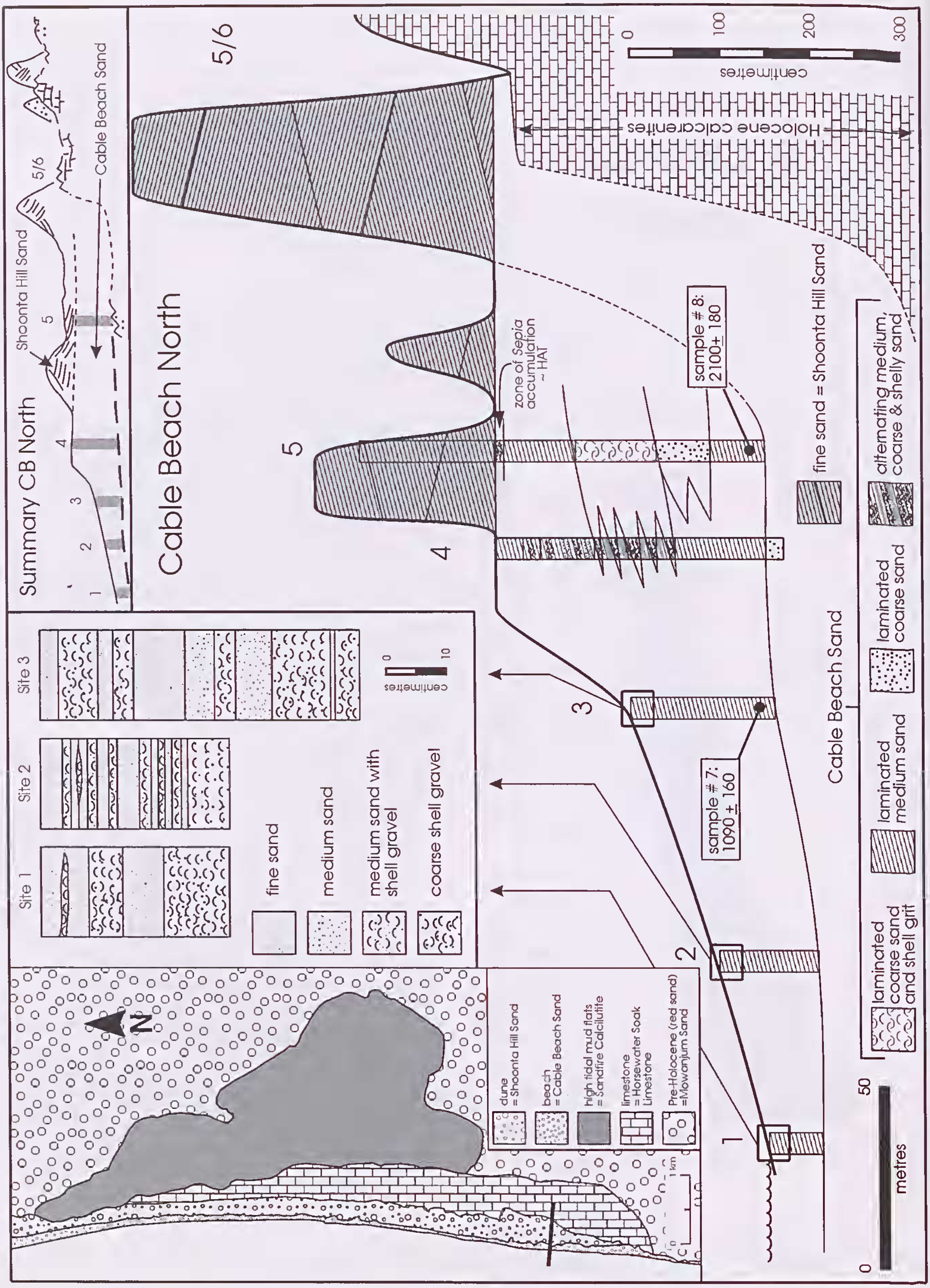
Members within the Formation:

Two members are formally recognised within the Formation: the Cape Boileau Calcarenite Member, and the Lombadina Conglomerate Member.

The Cape Boileau Member is the (beachrock) indurated portions of the Formation (Figure 8). Its type section is at Cape Boileau, where there is a 1-metre thick occurrence of beachrock plastered on Pleistocene limestone. It is composed of interlaminated coarse, medium and fine-grained calcarenite, with shell beds, and pebble beds. Locally, earlier cycles of induration and erosion are preserved as breccia and conglomerate beds embedded in the beachrock. The member is well developed and widespread, though patchy in its occurrence along the coast. Where well developed and concomitantly stripped of surface sand, the member is exposed as a rock pavement (Figure 8).

The Lombadina Conglomerate Member is the unit that has formed as a result of beachrock being reworked and deposited as boulders, cobbles, and pebbles, usually in rounded slab form. It commonly occurs in the upper tidal to storm level of the beach (Figures 7A and 8) and is

◀ **Figure 12.** Stratigraphic profiles exposed as cliffs along the western shore of Willie Creek, determined by augering across the tidal flat. Type sections of Horsewater Soak Calcarenite, Kennedys Cottage Limestone, and Willie Creek Calcarenite.



Summary CB North
Shoonta Hill Sand
Cable Beach Sand
5/6
Cable Beach North
Site 1
Site 2
Site 3
fine sand
medium sand
medium sand with shell gravel
coarse shell gravel
centimetres
dune =Shoonta Hill Sand
beach =Cable Beach Sand
high tidal mud flats =Sandfire Calcilutite
limestone =Horsewater Soak Limestone
Pre-Holocene (red sand) =Mowanjum Sand
1 km
zone of Sepia accumulation ~ HAT
sample # 8: 2100± 180
sample # 7: 1090 ± 160
Holocene calcarenites
fine sand = Shoonta Hill Sand
Cable Beach Sand
laminated coarse sand and shell grit
laminated medium sand
laminated coarse sand
alternating medium, coarse & shelly sand
metres

intermittently formed along the coast. It is well developed in the Lombadina area from where it derives its name. It may rest directly on a beachrock pavement or on the upper parts of a sandy beach or may be embedded and partly buried by laminated beach sand (Figure 8).

Discussion:
The Cable Beach Sand is a distinctive, widespread unit formed in high energy mid- to high tidal beach environments. On some eroding coasts, or headlands, it may form a veneer in the beach zone. The Formation also has variable lithology dependent on setting; depending on source materials, it varies from quartz-rich to carbonate-rich, and bioclast-dominated to ooid-dominated. However, overall, it tends to be a quartz and carbonate sand lithology. The other unifying feature of the Formation is its light-coloured nature and beach-face suite of sedimentary structures.

Port Smith Sand

Definition and characteristics:
The Port Smith Sand is the name proposed for the grey bioturbated to structureless sand and shelly sand, and locally brown/tan/buff laminated to cross-laminated sand that occurs in the low tidal zone along the Canning Coast.

Derivation of name:
Port Smith, latitude/longitude coordinates 18° 30' 16" S, 121° 47' 51" E, LaGrange 1:250,000 Topographical Sheet.

Type section (Type locality):
Coastal zone of Port Smith, latitude/longitude coordinates 18° 30' 51" S, 121° 48' 06" E, LaGrange 1:250,000 Topographical Sheet.

Distribution:
The unit occurs along almost the entire length of the Canning Coast. Additionally, it has been intersected, underlying other Holocene units, in numerous cores throughout the region.

Thickness and geometry:
Where intersected in cores and trenches, the Formation has been recorded as 1–2 m thick. Geomorphic considerations, *i.e.*, slope of the exposure of the Formation, suggests that it may be up to 3 m thick. Regionally, the unit is a ribbon, some hundreds of kilometres long, but only up to 10 km wide and 1–3 m thick.

Lithology:
Mostly grey, bioturbated to structureless, fine and very fine sand and shelly sand ranging to coarse sand and shelly sand. Sand grains are quartz, or quartz and bioclasts, and locally ooids (Figures 7F and 7G). Locally, there are thin layers of oriented shell. Where reworked by tides into megaripples (*e.g.*, the shore face at Mandora, or low tidal flats at Port Smith), there is a facies variant within the Formation, and sediments may consist of brown/tan/buff to grey layered and cross-laminated sand and shelly sand in addition to the dominant grey structureless to bioturbated sand.

The type section, along the shore face at Port Smith, consists of:

Description	Thickness
grey sand, bioturbated, scattered shell	30 cm
shell layer in grey sand	2 cm
grey, slightly shelly sand, structureless	75 cm
shell bed in grey sand	5 cm
grey, slightly shelly sand, structureless	30 cm

The top of this section is the modern tidal flat surface at about MLWN.

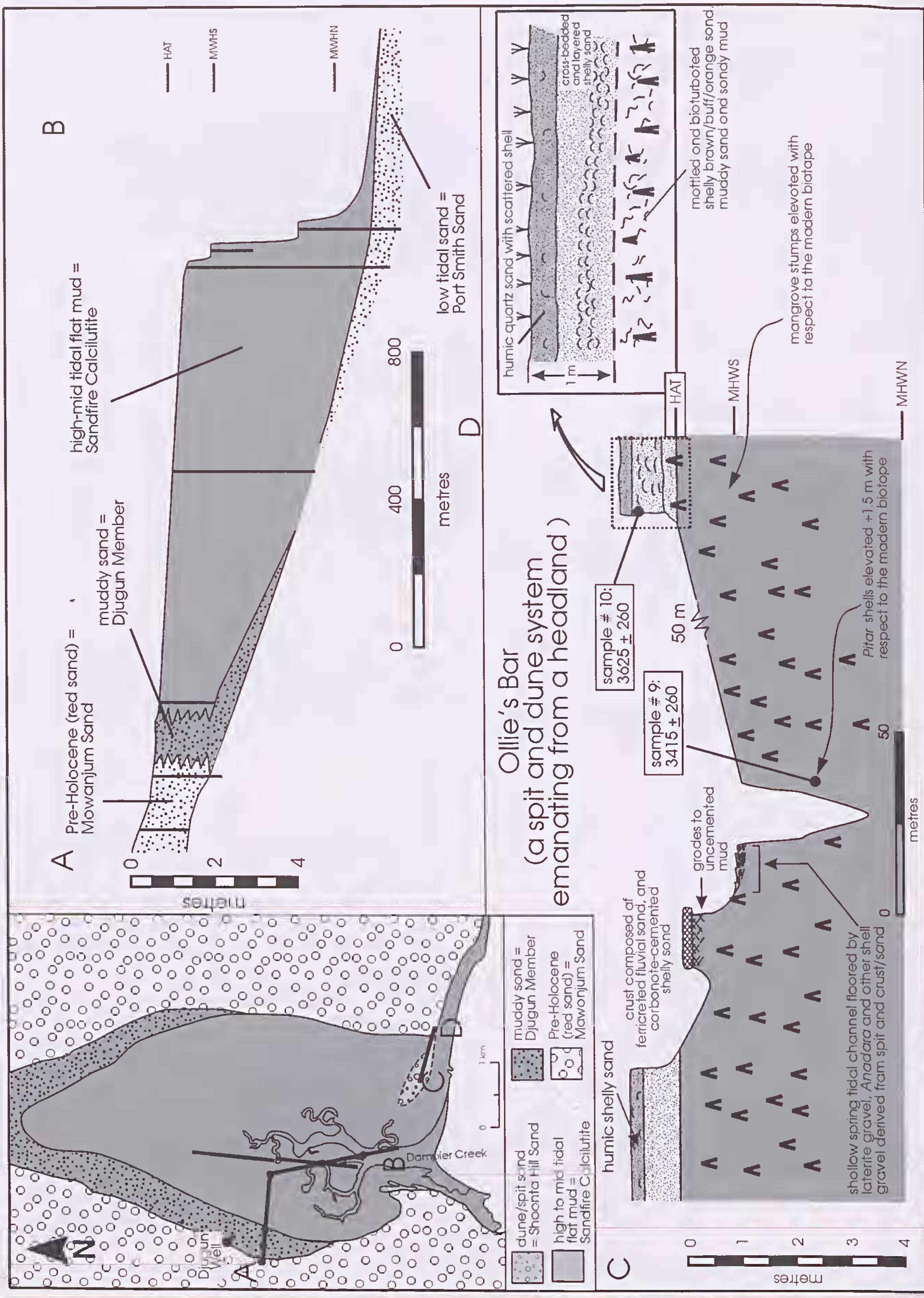
Supplementary section along the shore face at Mandora, with the top of the section located at MLWN, consists of:

Description	Thickness
Cable Beach Sand	100 cm
randomly-oriented shells in a shell gravel	
Port Smith Sand	

Stratigraphic relationships:
The unit is overlain, with gradational contact, by the Eighty Mile Beach Coquina, or Cable Beach Sand (Figures 25–27), or passes vertically upwards sharply or through a series of thin muddy interlayers over an interval of 50 cm, into the Sandfire Calcilutite (Figures 15, 21, 24–27).

Fauna:
Molluscan shells in the Formation include: the bivalves *Anadara crebricostata, Anomalocardia squamosa, Antigona* cf. *chemnitzii, Antigona chemnitzii, Arca avellana, Arca ventricosa, Asaphis violascens, Asaphis* sp., *Austriella sordida, Barbatia coma, Callista impar, Cardita* cf. *preissii, Dosinia incisa, Dosinia scalaris, Exotica assimilis, Hemidonax arafurensis, Irus* sp., *Mactra abbreviata* cf. *meretriciformis, Mactra westralis, Meropesta nicobarica, Paphies striata, Placamen gravescens, Saccostrea cucullata, Septifer bilocularis, Sunetta perexcavata, Tellina rostrata, Trachycardium flavum, Trisidos tortuosa,* and an unidentified Mesodesmatid, and the gastropods *Amalda elongata, Astraea rotularia, Calthalotia strigata, Cerithidea reidi, Chicoreus permestus, Conus victoriae, Cronia aurantiaca, Cymatium vespaceum, Cypraea gracilis, Nerita undata, Phalium areola, Phasianella australis, Pyrene varians, Pythia* cf. *scarabaeus, Strombus campbelli, Syrinx aruanus, Tectus fenestratus, Trochus maculatus,* and *Turbo bruneus.* The assemblages in this Formation, depending on how much transport has taken

◀ **Figure 13.** Stratigraphic profile across the shore of Cable Beach showing lithologic variability of the Cable Beach Sand. This area is the type section of the Cable Beach Sand.


A
B
C
D
high-mid tidal flat mud = Sandfire Calcilutite
muddy sand = Djugun Member
Pre-Holocene (red sand) = Mowanjum Sand
low tidal sand = Port Smith Sand
HAT
MWHS
MWHN
0 2 4 metres
0 400 800 metres
Ollie's Bar (a spit and dune system emanating from a headland)
sample # 10: 3625 ± 260
sample # 9: 3415 ± 260
50 m
humic quartz sand with scattered shell
cross-bedded and layered shelly sand
1 m
mottled and bioturbated shelly brown/buff/orange sand, muddy sand and sandy mud
mangrove stumps elevated with respect to the modern biotope
Pitar shells elevated +1.5 m with respect to the modern biotope
HAT
MHWS
MHWN
humic shelly sand
crust composed of ferricreted fluvial sand, and carbonate-cemented shelly sand
grades to uncemented mud
shallow spring tidal channel floored by laterite gravel, Anadara and other shell gravel derived from spit and crust/sand
0 50 metres
0 1 2 3 4 metres
N
Djugun Well
Dampier Creek
0 1 km
dune/spit sand = Shoonta Hill Sand
high to mid tidal flat mud = Sandfire Calcilutite
muddy sand = Djugun Member
Pre-Holocene (red sand) = Mowanjum Sand

place from other environments, mostly form autochthonous biocoenoses or mixed biocoenoses/ thanatocoenoses.

Age:
Radiocarbon dating of shells within the Formation places it in the Holocene, *viz.*, 3520 ± 200 yrs BP, 3680 ± 210 yrs BP, and 4320 ± 220 yrs BP (Table 6, and Figures 26 and 27).

Discussion:
The Port Smith Sand is a distinctive and widespread grey sand and shelly sand unit formed in sandy low tidal flat environments. As such it will be a basal Holocene unit to many of the stratigraphic sequences in this region. The diagnostic lithological feature of the Formation is its grey nature, shell content, and its biogenic sedimentary structures. This Formation may differ in its lithology dependent on setting from quartz-rich to carbonate-rich due to variation in source materials, however; in general, it is a quartzose and calcareous sand. It also varies from being dominantly bioturbated grey sand and shelly sand to locally laminated and cross-laminated where waves and tidal currents have reworked the surface.

Sandfire Calcilutite

Definition and characteristics:
The Sandfire Calcilutite is the name proposed for the dominantly light-coloured to white (cream, white to grey), structureless to bioturbated to laminated calcilutite that occurs along the Canning Coast. The Formation varies lithologically from cream structureless calcilutite, to root-structured, bioturbated, mangrove stump-bearing, shelly cream and grey calcilutite, to laminated cream calcilutite and shelly calcilutite, to indurated cream calcilutite, to muddy calcilutaceous muddy sand. These lithological variations are the bases for separating various members within the Formation (see later in this paper).

Derivation of Name:
Sandfire, a location south of Broome, latitude/ longitude coordinates 19° 43' 54" S, 121° 12' 31" E, Mandora 1:250,000 Topographical Sheet, where the Formation is well developed. "Sandfire" is a literary degradation of the term samphire, as in the locally named Samphire Marsh, so named because the lowlands in this region are inhabited by samphires. Samphire Marsh is also known as Mandora Marsh, the latter name being used in the listing of the marsh as a Ramsar site.

Type section (Type locality):
The Sandfire region, latitude/longitude coordinates 19° 43' 54" S, 121° 12' 31" E, Mandora 1:250,000 Topographical Sheet.

Distribution:
The unit is widespread along the Canning Coast, occurring from Beagle Bay to Pardoo Creek. It also has been intersected in numerous cores throughout the region.

Thickness and geometry:
Generally as the lithotope for this Formation occurs between MSL and HAT, in northern areas where the tidal range is 8 m, the Formation has been intersected in cores and trenches and has been recorded at 5 m thick. In southern areas where the tidal range is 6 m, the Formation is 2–3 m thick. In Crab Creek it is 10 m thick. At its type location it is at least 7 m thick. Regionally, the unit will appear as discontinuous ribbons and lenses, some kilometres to tens of kilometres in length and kilometres to tens of kilometres width, but only 2–7 m thick, increasing in general thickness in response to increasing tidal amplitude, from south to north.

Lithology:
Light-coloured to white, cream to grey bioturbated to structureless to locally root-structured to laminated calcilutite and shelly calcilutite. XRD analyses show the mud to be dominantly calcite, with some Mg-calcite and aragonite, and generally minor quartz silt and kaolinite. SEM images show the mud to be silt to clay sized, and composed of fragments of molluscs, foraminifera, and other carbonate, as well as fragments of sponge spicule and diatoms (Figures 7Q and 7R). In mangrove environments, there is a local scattered shell content, composed of mangrove-associated molluscs; in this lithotope, in some areas exposed to periodic wave action and storms, low tidal molluscs have been transported into the environment, and form a shelly calcilutite. Where the Formation extends as a depositional lithosome to low tidal levels, the sediment is more commonly laminated, and has a shell content (indicative of mid-low tidal settings) different to those of mangrove environments. While there is lithological variation within the Formation that enables differentiation of members (see later), the type section has been selected as the sequence that is the most ubiquitous and common as a lithological unit. The type section consists of:

Description	Thickness
cream structureless calcilutite	700 cm

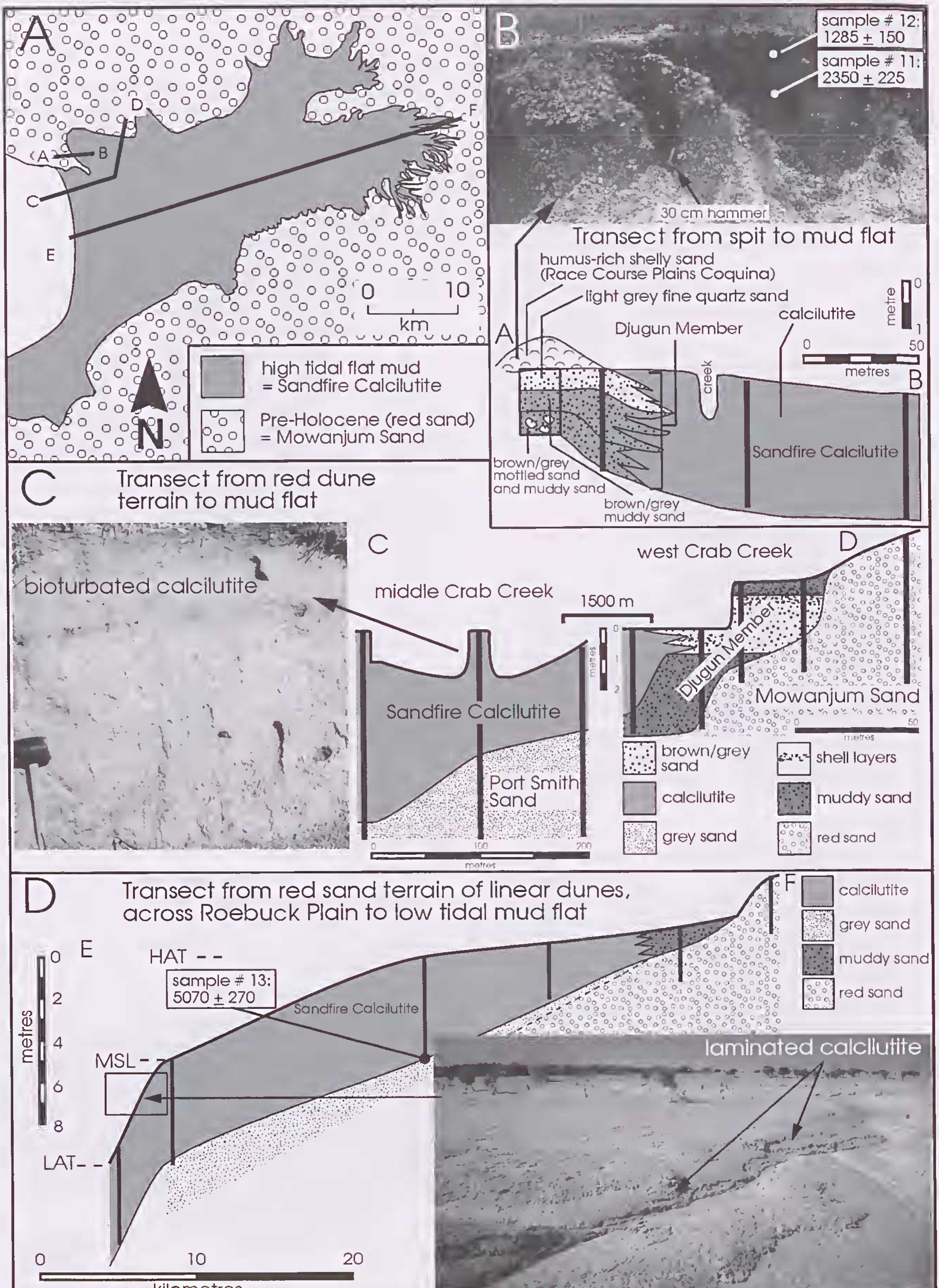
The top of this section is the marsh surface located about 2 m above HAT.

A supplementary section at Crab Creek consists of:

Description	Thickness
cream structureless calcilutite, with scattered shell	400 cm
cream calcilutite	200 cm
grey sand of the Port Smith Sand	

The top of this section is the samphire surface located at about EHWS.

◀ **Figure 14.** Stratigraphic profiles in the Dampier Creek area exposed as cliffs cut into a spit/dune, and cliffs along creek banks. Profile A–B determined by augering and exposure along creek banks.


A
D
F
A
B
C
E
0
10
km
N
high tidal flat mud
= Sandfire Calcilutite
Pre-Holocene (red sand)
= Mowanjum Sand
B
sample # 12:
1285 ± 150
sample # 11:
2350 ± 225
30 cm hammer
Transect from spit to mud flat
humus-rich shelly sand
(Race Course Plains Coquina)
light grey fine quartz sand
calcilutite
Djugun Member
metre
0
1
0
50
metres
A
B
creek
Sandfire Calcilutite
brown/grey
mottled sand
and muddy sand
brown/grey
muddy sand
C
Transect from red dune
terrain to mud flat
bioturbated calcilutite
C
middle Crab Creek
west Crab Creek
D
1500 m
metres
0
1
2
Djugun Member
Sandfire Calcilutite
Port Smith
Sand
Mowanjum Sand
0
100
200
metres
0
50
metres
brown/grey
sand
shell layers
calcilutite
muddy sand
grey sand
red sand
D
Transect from red sand terrain of linear dunes,
across Roebuck Plain to low tidal mud flat
F
calcilutite
grey sand
muddy sand
red sand
E
HAT
sample # 13:
5070 ± 270
Sandfire Calcilutite
metres
0
2
4
6
8
MSL
LAT
laminated calcilutite
0
10
20
kilometres

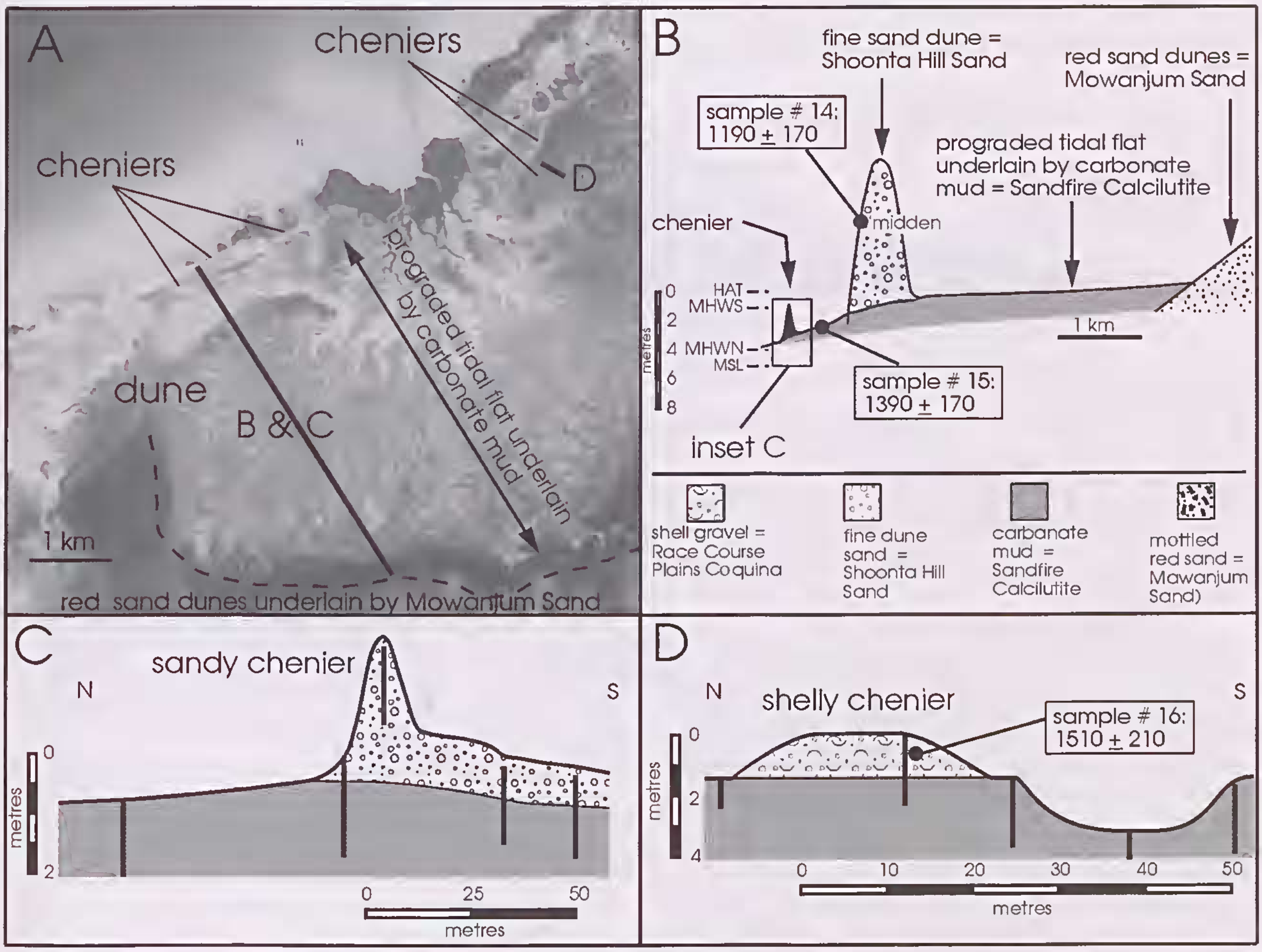


Figure 16. Dunes and cheniers and their relationship to tidal flat mud in the Thangoo area. Sites for samples collected for radiocarbon analysis are shown.

Other supplementary sections are illustrated in Figures 10–12, 14–16, 21, 23–27 and 29–30).

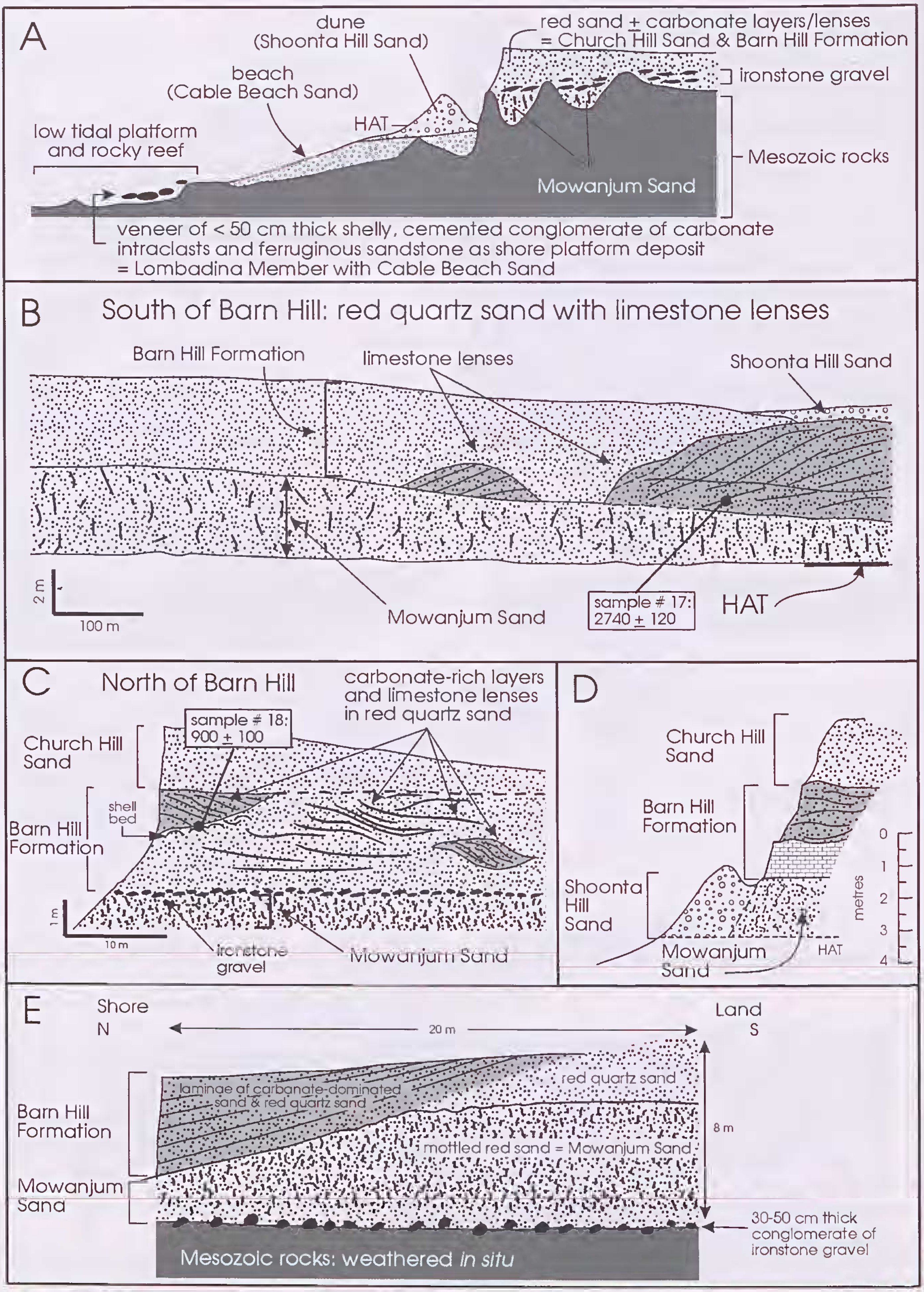
The older parts of the Formation, or where the Formation adjoins sites of freshwater discharge onto tidal flats, may be indurated.

The sedimentary imprints and the synsedimentary and early diagenetic changes that have occurred and that are occurring in the Formation are shown in Figure 9 to illustrate the relationship of the various members in the Formation.

Stratigraphic relationships:
Stratigraphic relations have been determined from a number of locations. The unit passes downwards, with gradational contact, through a series of muddy interlayers over an interval of 30 cm, into the underlying Port Smith Sand. Where it is juxtaposed against the Race Course Plains Coquina, the basal contact is sharp. Locally, there is an erosional contact with the laterally equivalent Eighty Mile Beach Coquina (Figures 25–27). It passes laterally and basally into red sand of the Mowanjum Sand *via* a muddy sand zone (the Djugun Member).

Fauna and flora:
Molluscan shell remains in the upper parts of the Formation include the bivalves *Dosinia* sp., *Pitar* sp, *Saccostrea cucullata, Venus lamellaris,* and the gastropods *Cassidula angulifera, Cerithidea anticipata, Cerithidea cingulata, Ellobium aurisjudae, Nerita undata, Telescopium telescopium, Terebralia palustris* and *Terebralia sulcata,* and remains of Teredinidae ("shipworm"). Plant remains include *in situ* and fallen trunks and wood fragments of *Avicennia marina, Rhizophora stylosa* and *Ceriops tagal.* The upper part of the formation comprises an autochthonous biocoenosis. Molluscan shell remains in the middle to lower parts of the Formation include the bivalves *Anadara granosa, Anomalocardium squamosa, Paphies striata, Tellina capsoides, Tellina piratica, Tellina* spp, and the gastropod *Nassarius dorsatus.* The lower part of the formation also comprises an autochthonous biocoenosis. Determining the full diversity of invertebrate fauna of the middle to

◀ **Figure 15.** Stratigraphic profiles of Roebuck Plains, determined by augering and from cliff exposures along creek banks, showing relationship of Sandfire Calcilutite to Mowanjum Sand, and the occurrence of Djugun Member between Sandfire Calcilutite and Mowanjum Sand.


A
dune
(Shoonta Hill Sand)
red sand + carbonate layers/lenses
= Church Hill Sand & Barn Hill Formation
beach
(Cable Beach Sand)
ironstone gravel
HAT
low tidal platform
and rocky reef
Mesozoic rocks
Mowanjum Sand
veneer of < 50 cm thick shelly, cemented conglomerate of carbonate
intraclasts and ferruginous sandstone as shore platform deposit
= Lombadina Member with Cable Beach Sand
B
South of Barn Hill: red quartz sand with limestone lenses
Barn Hill Formation
limestone lenses
Shoonta Hill Sand
2 m
100 m
Mowanjum Sand
sample # 17:
2740 ± 120
HAT
C
North of Barn Hill
carbonate-rich layers
and limestone lenses
in red quartz sand
sample # 18:
900 ± 100
Church Hill
Sand
shell
bed
Barn Hill
Formation
1 m
10 m
ironstone
gravel
Mowanjum Sand
D
Church Hill
Sand
Barn Hill
Formation
Shoonta
Hill
Sand
metres
0
1
2
3
4
HAT
Mowanjum
Sand
E
Shore
N
Land
S
20 m
laminae of carbonate-dominated
sand & red quartz sand
red quartz sand
Barn Hill
Formation
8 m
mottled red sand = Mowanjum Sand
Mowanjum
Sand
30-50 cm thick
conglomerate of
ironstone gravel
Mesozoic rocks: weathered in situ

lower tidal flats of the biotope/lithotope of the Sandfire calcilutite was not the primary objective of this study, and the species list above is provided to characterise the lower part of the Formation. However, some detailed inventory work has been carried out specifically in the northern Roebuck Bay area, and the reader is directed to Pepping *et al.* (1999) for a more comprehensive list of invertebrate fauna inhabiting middle to low tidal zones of the mud flats at Roebuck Bay.

Age:
Radiocarbon dating of shells and sediment within the Formation places it in the Holocene, *viz.*, 1390 ± 170 yrs BP, 3170 ± 180 yrs BP, 3170 ± 130 yrs BP, 3415 ± 260 yrs BP, 4070 ± 220 yrs BP, 4470 ± 120 yrs BP, 5070 ± 270 yrs BP, 7280 ± 290 yrs BP, 7450 ± 190 yrs BP (Table 6, and Figures 14–16, 23–24, 27 and 29–30).

Members within the Formation:
Three members are formally recognised within the Formation: the Lagrange Calcilutite Member, the Crab Creek Calcilutite Member, and the Djugun Member.

The Lagrange Calcilutite Member is a grey root-structured to burrow-structured to bioturbated calcilutite with *in situ* mangrove stumps and other mangrove debris, and scattered mangrove habitat shells; it grades to shell-free calcilutite (Figure 9). In its primary form it carries a signature of having been formed under mangrove cover, but with diagenesis (dissolution and oxidation), in spite of its distinctive structures and robust shell content, the lithology transforms progressively to a cream, structureless to bioturbated calcilutite. The member is up to 4 m thick. The type location for the member is the mid- to high tidal flats of Lagrange Bay.

The Crab Creek Calcilutite Member is a grey laminated to burrow-structured to bioturbated calcilutite with a generally autochthonous assemblage of *in situ* bivalve shells, articulated and disarticulated bivalves, fragmented bivalves, and scattered gastropods. Disarticulated shells and shell fragments often occur in layers, probably a result of storm concentration, with winnowing away of mud. The primary lithology of laminated shelly calcilutite grades to sparsely shelly calcilutite (Figure 9). In its primary form it carries a signature of having been deposited under middle to low tidal flats, but with diagenesis (dissolution and oxidation), the lithology can transform progressively to a cream bioturbated sparsely shelly calcilutite. Initially, tellinid shells are abundant, but being relatively thin, they are readily fragmented, particularly biogenically, and are commonly reduced to fragments. The member generally is up to 5 m thick, but locally in the seaward parts of mud-filled tidal channels and ebb-tidal fans at the mouths of tidal creeks, it can be up to 8 m thick. The type location for the member is seaward of Crab Creek, east of Broome. Its variation in thickness laterally is due to its occurrence different environmental/physiographic settings, *e.g.*, the more sheltered parts of large embayments such as in the re-entrant bay of northern Roebuck Bay, or in ebb-tidal fans at the mouths of tidal creeks.

The Djugun Member is the unit formed as a transitional lithology between Sandfire Calcilutite and Mowanjum Sand. As such, it is a bioturbated calcilutaceous muddy sand, varying to kaolinitic calcilutaceous muddy sand. Locally, there are sand layers. The member is 0.3–2.0 m thick

The relationship between the three members is shown in Figure 9.

Discussion:
The Sandfire Calcilutite is a distinctive, widespread cream to grey calcilutite unit formed mainly in low energy mid-high tidal mangrove vegetated environments, but accumulation of the lithosome locally may extend to muddy tidal flats in front of mangrove zones between MSL and low tidal levels.

Race Course Plains Coquina

Definition and characteristics:
The Race Course Plains Coquina is the name proposed for the light-coloured oligomictic coquina that forms shoe-string deposits as cheniers and spits along the high-tidal to supratidal flats along the Canning Coast.

Derivation of Name:
Race Course Plains, on the Thangoo Station, latitude/longitude coordinates 18° 13' 06" S, 122° 14' 22" E, Lagrange 1:250,000 Topographical Sheet.

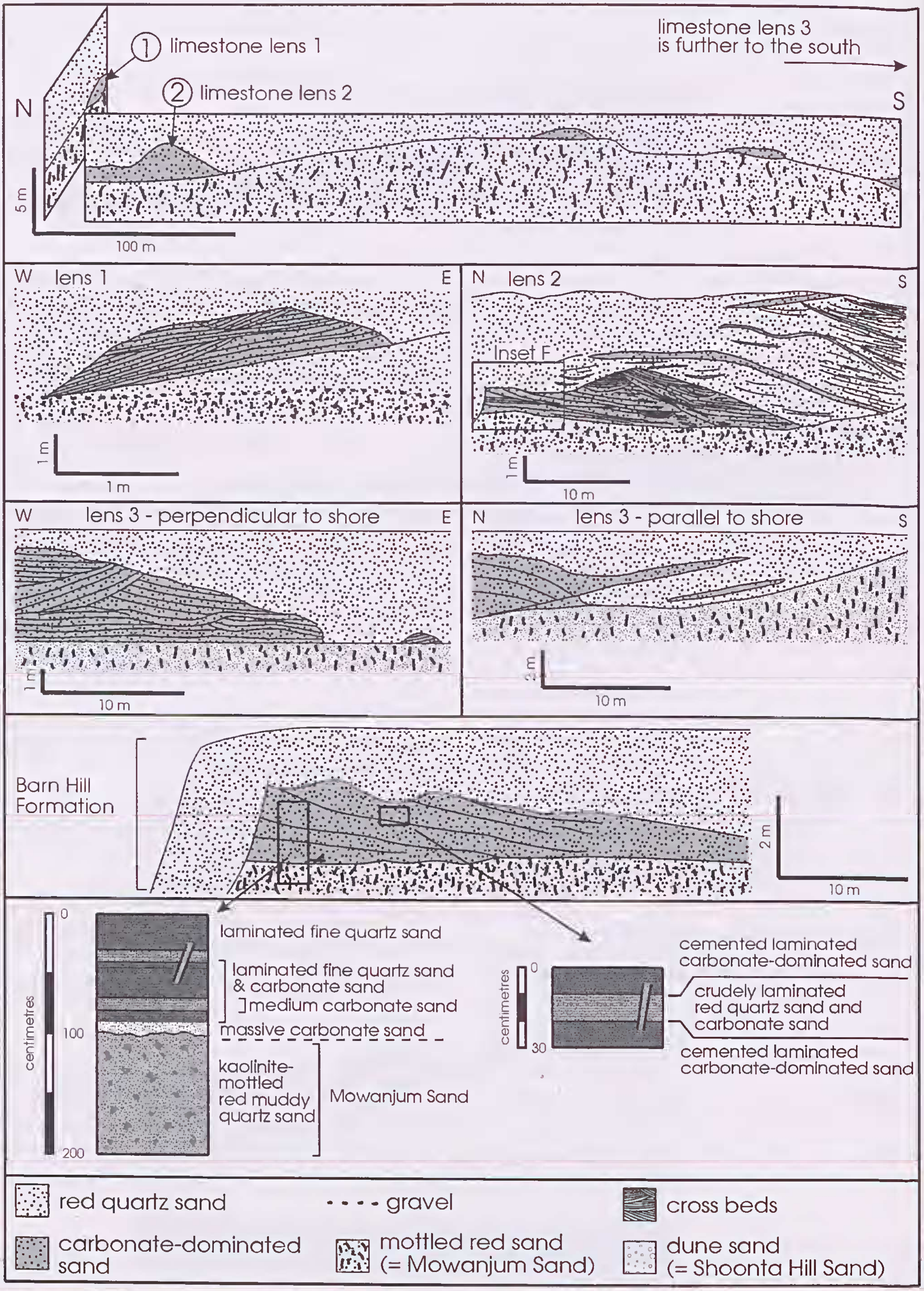
Type section (Type locality):
Quarry Pit on Thangoo Station, latitude/longitude coordinates 18° 13' 07" S, 122° 15' 31" E, Lagrange 1:250,000 Topographical Sheet.

Distribution:
The unit is widespread along the Canning Coast as a semi-continuous to scattered shoe-string deposit.

Thickness and geometry:
Where intersected in cores and trenches, the Formation has been recorded as 2 m thick. Regionally, the unit will appear as discontinuous shoe-string deposits, individually, some tens of metres to several kilometres long, but only up to tens of metres wide and 2 m thick.

Lithology:
In general, light-coloured, shell gravel, shelly sand, and some sand that is variable in structure from bedded, to laminated, to cross-laminated, to locally bioturbated, to structureless. It is biostratigraphically distinct in that it is dominated by shells of *Anadara*, *Terebralia*, *Saccostrea*

◀ **Figure 17.** Stratigraphic profiles of the Barn Hill area determined from cliff exposures showing relationship between Mesozoic rocks, Mowanjum Sand, Barn Hill Formation, Church Hill Sand, and Shoonta Hill Sand. This area is the type section of the Barn Hill Formation.



limestone lens 1
limestone lens 2
limestone lens 3
is further to the south
N
S
5 m
100 m
W
lens 1
E
1 m
1 m
N
lens 2
S
Inset F
1 m
10 m
W
lens 3 - perpendicular to shore
E
1 m
10 m
N
lens 3 - parallel to shore
S
10 m
Barn Hill
Formation
2 m
10 m
centimetres
0
100
200
laminated fine quartz sand
laminated fine quartz sand
& carbonate sand
medium carbonate sand
massive carbonate sand
kaolinite-
mottled
red muddy
quartz sand
Mowanjum Sand
centimetres
0
30
cemented laminated
carbonate-dominated sand
crudely laminated
red quartz sand and
carbonate sand
cemented laminated
carbonate-dominated sand
red quartz sand
gravel
cross beds
carbonate-dominated
sand
mottled red sand
(= Mowanjum Sand)
dune sand
(= Shoonta Hill Sand)

cucullata, and *Cerithidea*. Figure 7C shows a shell gravel dominated by fragments of *Saccostrea cucullata*. The type section consists of:

Description	Thickness
shell gravel, layered shell hash and sand; sharp contact with underlying Sandfire Calcilutite	150 cm

The top of the Formation at this section is the ground surface located at HAT.

Stratigraphic relationships:
The unit passes downwards, with sharp contact, into the underlying Sandfire Calcilutite. It interfingers locally with Sandfire Calcilutite on its margins (Figures 15 and 16).

Fauna:
The diversity of molluscan shells in the Formation is variable: it depends on location, and on whether storm/wave processes have been dominant in accumulating the shells or whether Indigenous people have been dominant in generating middens, or both processes have occurred. Progressing from south to north along the Race Course Plains, four cheniers were sampled for shelly fauna. In chenier 1, the shell deposits are dominated by bivalves deposited by storms/waves, with lesser input by Indigenous people, and are composed of bivalves *Anadara granosa, Anadara crebricostata, Anadara secticostata, Asaphis violascens, Dosinia deshayesii, Dosinia incisa, Gafrarium dispar, Mactra incarnata, Paphia crassisula*, and *Saccostrea cucullata*, and gastropods *Cantharus* cf. *erythrostoma, Cerithidea anticipata, Cerithidea* cf. *cingulata, Cerithidea cingulata, Chicoreus cornucervi, Cymatium waterhousei, Epitonium imperialis, Littoraria* cf. *cingulata, Nassarius dorsatus, Nerita squamulata, Neritina* cf. *violacea, Phalium areola, Polinices* sp., *Stramonita javanica, Terebralia palustris, Turbo laminiferus*, and unidentified Marginellids. The assemblage is an allochthonous thanatocoenosis. In chenier 2, the shell deposits are dominated by those accumulated by storms/waves, with some input by Indigenous people; the shell deposits are composed of the bivalves *Anadara granosa, Dosinia incisa*, and *Tellina* cf. *piratica*. The assemblage also is an allochthonous thanatocoenosis. In chenier 3, the shells are dominated by those deposited by storms/waves, with some contribution by Indigenous people; the shell deposits are composed of the bivalves *Anadara granosa, Dosinia incisa*, and *Saccostrea cucullata*. The assemblage is an allochthonous thanatocoenosis. In chenier 4, the coquina gravel is dominated by entire shells and fragments of *Saccostrea cucullata* that have been transported and deposited by storms/waves. The assemblage is an allochthonous partial biocoenosis.

Age:
Radiocarbon dating of shells within the Formation places it in the Holocene, *viz.*, 1285 ± 150 yrs BP, 2290 ± 180 yrs BP, 1510 ± 210 yrs BP, 2350 ± 225 yrs BP, 3625 ± 260 yrs BP (Table 6, and Figures 14–16).

Discussion:
The Race Course Plains Coquina is a distinctive and widespread shell gravel unit formed in high energy, mid- to high-tidal, to suptratidal settings through the agencies of cyclones, storms and wave reworking of shell deposits and their transport into mangrove settings, and by addition of shells as middens by Indigenous people.

Cape Gourdon Formation

Definition and characteristics:
The Cape Gourdon Formation is the name proposed for the discontinuous lensoid deposits of bedded and laminated to cross-laminated interlayered red, orange and white quartz and quartz-and-carbonate sand, and locally gravelly sand, with small limestone lenses, formed as supratidal shoreline alluvial fans and dunes along the Canning Coast.

Derivation of Name:
After Cape Gourdon, latitude/longitude coordinates 18° 24' 22" S, 122° 01' 39" E, Lagrange 1:250,000 Topographical Sheet.

Type section (Type locality):
Cliff exposure on coast near Cape Gourdon, latitude/longitude coordinates 18° 21' 52" S, 122° 02' 13" E, Lagrange 1:250,000 Topographical Sheet.

Distribution:
The unit is widespread in the region as a semi-continuous to scattered lensoid deposit where Mowanjum Sand crops out at the coast.

Thickness and geometry:
Where exposed along the coast, the Formation has been recorded as up to 1.5 m thick. Regionally, the unit will appear as discontinuous lensoid deposits, individually, some tens of metres to several hundred of metres long, but only up to 100 m wide and 1.5 m thick.

Lithology:
In general, a bedded and laminated to cross-laminated interlayered red sand varying to orange quartz and quartz-and-carbonate sand (depending on carbonate sand content), and locally gravelly sand, and small limestone lenses composed of calcarenite; sand grains of carbonate laminae and layers are bioclastic, carbonate-intraclast, carbonate-lithoclast, and oolitic.

◀ **Figure 18.** Stratigraphic profiles of the Barn Hill area determined from cliff exposures showing internal features of Barn Hill Formation, and showing stratigraphic relationship between Mowanjum Sand, Barn Hill Formation and Shoonta Hill Sand.

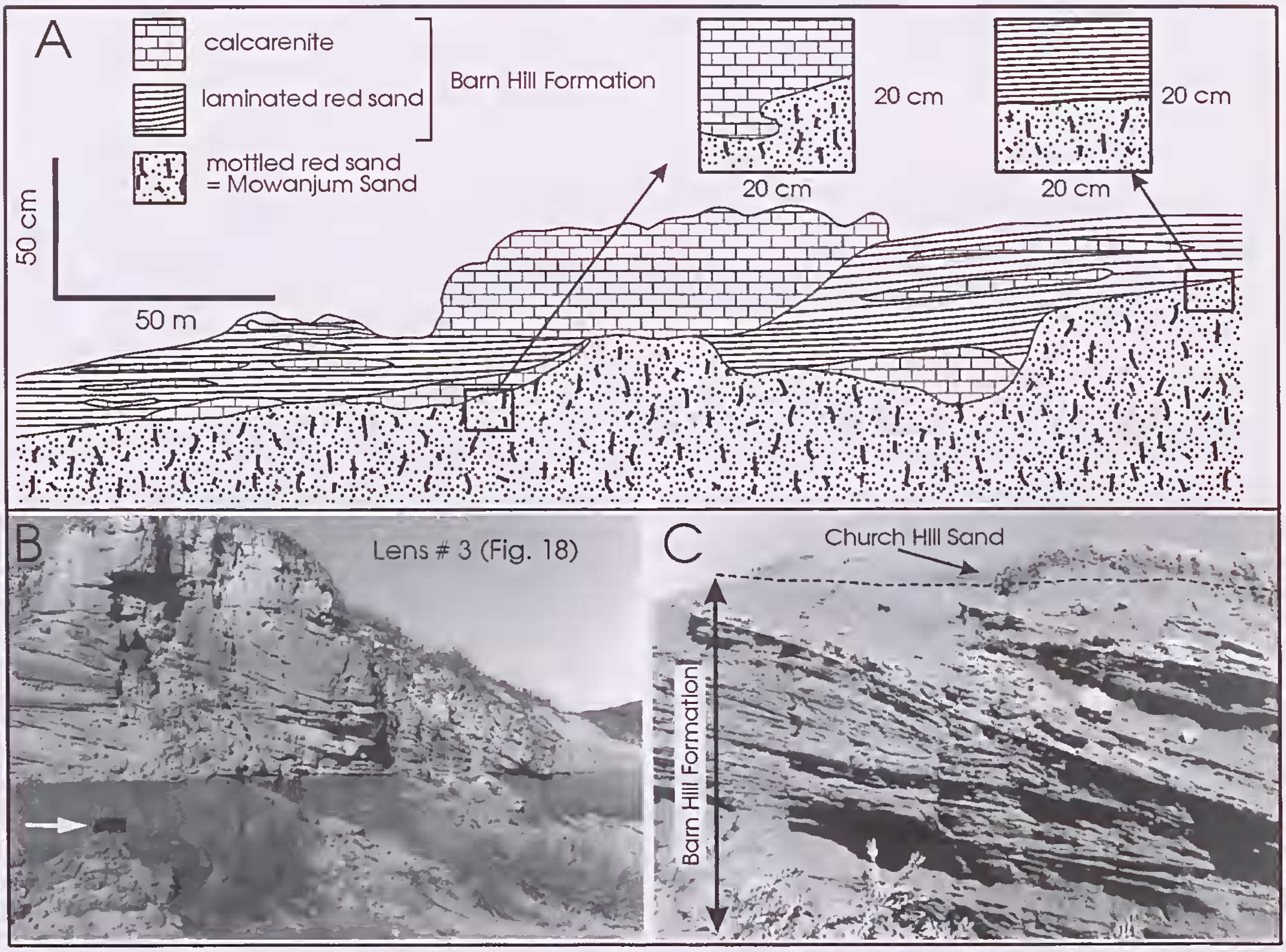


Figure 19. Stratigraphic profiles of Barn Hill area determined from cliff exposures. A. Limestone lenses within Barn Hill Formation. B. Photograph of cross laminated limestone lens resting with sharp contact on Mowanjum Sand. Clipboard (arrowed) is 30 cm long. C. Cross lamination within a limestone lens showing interlayering of carbonate-rich layers and red quartz-sand-rich layers. Church Hill Sand occurs at the top of the profile.

The type section, pit 4 along the transect shown in Figure 20, consists of:

Description	Thickness
structureless orange sand	5 cm
interbedded laminated red sand, laminated orange sand, and laminated white sand, with local cobble-sized intraclast of calcarenite	80 cm
white structureless sand	50 cm
structureless red muddy sand	10 cm

The top of this section is the modern alluvial fan surface. The base of the Formation at this section is located at *circa* HAT.

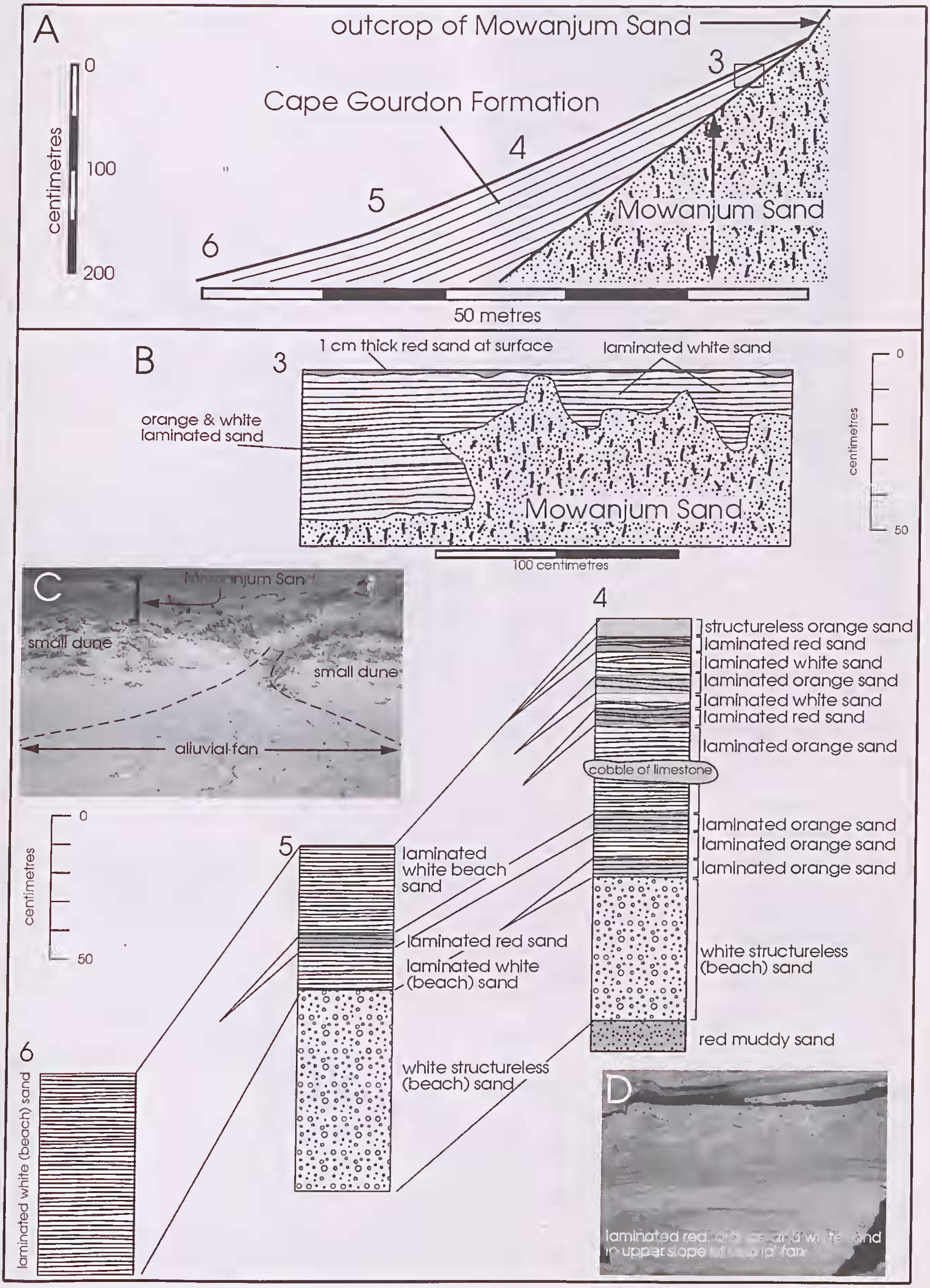
Stratigraphic relationships:

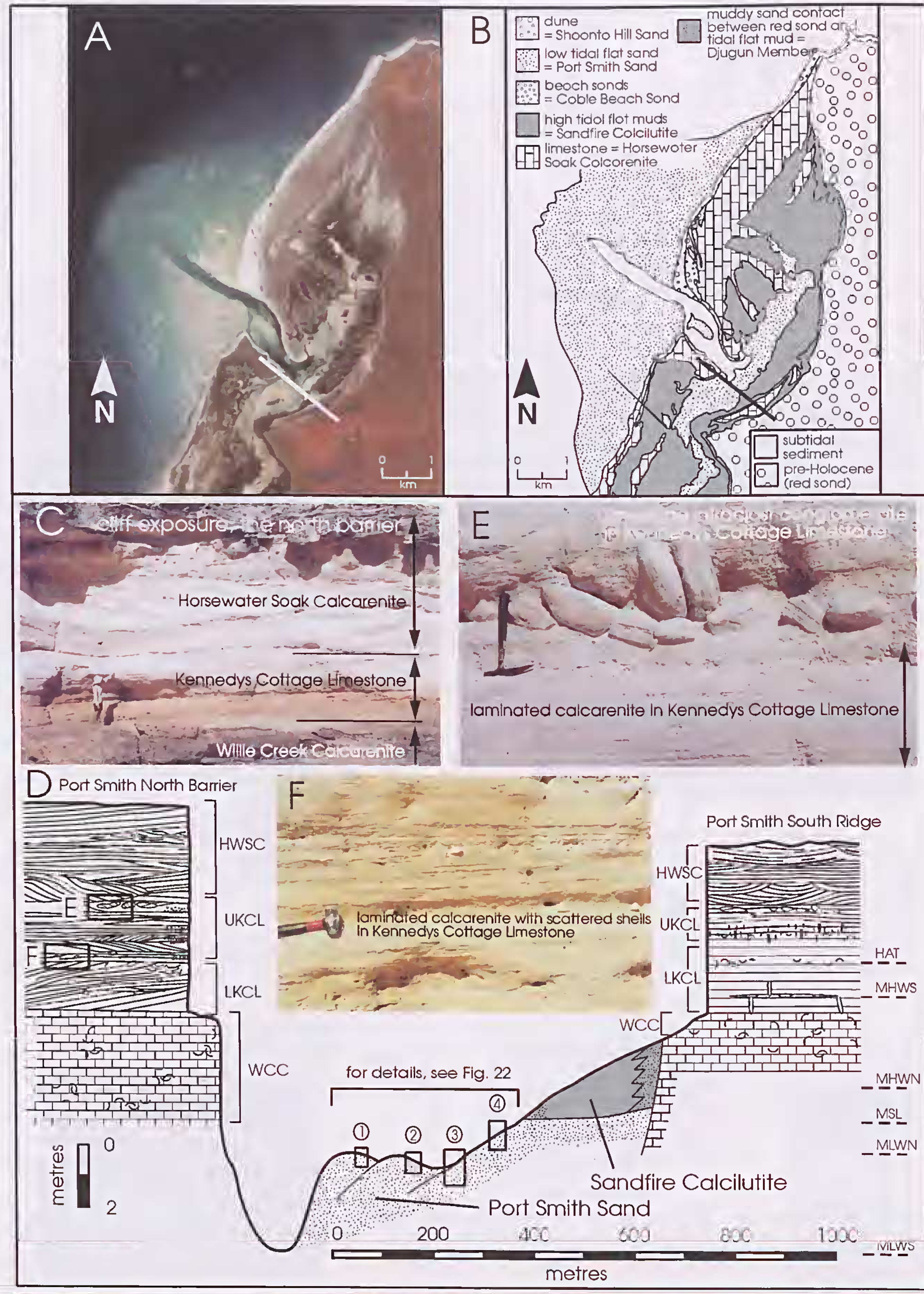
The unit rests, with sharp contact, on layered sand of the Cable Beach Sand, or interfingers with the Cable Beach Sand (Figure 20). It erosionally overlies and is cut into the Barn Hill Formation and the Shoonta Hill Sand. It overlies the Mowanjum Sand and Barn Hill Formation with sharp inclined to gullied contact (Figure 20). The Formation also is overlain by Shoonta Hill Sand with sharp contact.

Fauna:

Shells occur in some horizons within the Formation. *Donax faba* locally occurs in the lower parts of the Formation and have been delivered by wave run-up from the beach zone. Some shells (*Anadara granosa*) underlying limestone lenses appear to be middens. The midden is an allochthonous thanatocoenosis.

Figure 20. Stratigraphic profiles of the Cape Gourdon Formation in the Barn Hill area as determined from cliff exposures and by trenching. A. Overview of stratigraphic relationship of Cape Gourdon Formation to Mowanjum Sand along the length of an alluvial fan. B. Cape Gourdon Formation overlying an unconformity cut into Mowanjum Sand, and details of pit sections 4, 5 and 6 showing nature of lithologic layering within the Cape Gourdon Formation. C. Overview of alluvial fan deriving from a gully cut into the Mowanjum Sand.


A
outcrop of Mowanjum Sand
Cape Gourdon Formation
Mowanjum Sand
3
4
5
6
centimetres
0
100
200
50 metres
B
3
1 cm thick red sand at surface
laminated white sand
orange & white laminated sand
Mowanjum Sand
100 centimetres
centimetres
0
50
C
small dune
small dune
alluvial fan
4
structureless orange sand
laminated red sand
laminated white sand
laminated orange sand
laminated white sand
laminated red sand
laminated orange sand
cobble of limestone
laminated orange sand
laminated orange sand
laminated orange sand
white structureless (beach) sand
red muddy sand
5
laminated white beach sand
laminated red sand
laminated white (beach) sand
white structureless (beach) sand
centimetres
0
50
6
laminated white (beach) sand
D


A
N
0 1
km
B
dune = Shoonta Hill Sand
low tidal flat sand = Port Smith Sand
beach sands = Cable Beach Sand
high tidal flat muds = Sandfire Calcilutite
limestone = Horsewater Soak Calcarenite
muddy sand contact between red sand and tidal flat mud = Djugun Member
subtidal sediment
pre-Holocene (red sand)
N
0 1
km
C
cliff exposure, the north barrier
Horsewater Soak Calcarenite
Kennedys Cottage Limestone
Willie Creek Calcarenite
E
laminated calcarenite in Kennedys Cottage Limestone
D Port Smith North Barrier
HWSC
UKCL
LKCL
WCC
E
F
metres
0
2
F
laminated calcarenite with scattered shells in Kennedys Cottage Limestone
Port Smith South Ridge
HWSC
UKCL
LKCL
WCC
HAT
MHWS
MHWN
MSL
MLWN
MLWS
for details, see Fig. 22
①
②
③
④
Sandfire Calcilutite
Port Smith Sand
0
200
400
600
800
1000
metres

Age:
No radiocarbon ages have been obtained from the Formation, but contemporary sedimentation and stratigraphic relationships with the Shoonta Hill Sand, Cable Beach Sand, and Barn Hill Formation (all dated as Holocene) places the Formation within the Holocene.

Discussion:
The Cape Gourdon Formation is a distinctive unit formed where the Pleistocene Mowanjum Sand crops out and interacts with coastal processes. Red sand, remobilised by sheet wash along the coast from the Mowanjum Sand, forms alluvial fans along the shore. Holocene coastal sand dunes encroach from the shore onto the fans, and these also have been cut by alluvial fan sedimentation. The entire Formation is a complex of alluvial fan sedimentation (with material derived from Pleistocene desert dunes and from Holocene coastal dunes), coastal dune encroachment, and local cementation of carbonate layers in a tropical climatic setting.

Barn Hill Formation

Definition and characteristics:
The Barn Hill Formation is the name proposed for the structureless to laminated to cross-laminated red quartz sand and quartz-and-carbonate sand with large to small limestone lenses, limestone beds, and carbonate-rich sand laminae; it is a shoe-string to lensoid deposit formed as supratidal dunes along the Canning Coast.

Derivation of Name:
After Barn Hill, latitude/longitude coordinates 18° 21' 59" S, 122° 03' 01" E, Lagrange 1:250,000 Topographical Sheet.

Type section (Type locality):
Cliff exposure on coast near Barn Hill, latitude/longitude coordinates 18° 21' 53" S, 122° 02' 14" E, Lagrange 1:250,000 Topographical Sheet.

Distribution:
The unit is widespread along the Canning Coast as a semi-continuous to scattered shoe-string to lensoid deposit.

Thickness and geometry:
Where exposed, the Formation has been recorded as up to 7 m thick. Regionally, the unit will appear as discontinuous shoe-string and lensoid deposits, individually, some tens of metres to several hundred of metres long, but only up to 100 m wide and 7 m thick.

Lithology:
In general, a red sand varying to orange quartz and light coloured to orange quartz-and-carbonate sand (depending on carbonate sand content), with millimetre to centimetre thick laminae and beds of carbonate-rich sand, and large to small limestone lenses, 2–4 m thick and 1–50 m long, composed of calcarenite; sand grains of the carbonate laminae and layers are bioclastic, carbonate-intraclast, carbonate-lithoclast, and oolitic (Figures 7D and. 7P); the cementing agent in the calcarenite layers is sparry calcite (Figure 7P); sedimentary structures include lamination, cross-lamination, root-structured to structureless.

The type section (the profile of lens 2 of Figure 18) consists of:

Description	Thickness
red quartz sand of the Church Hill Sand	
red quartz sand with interlayered thick beds of calcarenite, 50 cm thick, thin beds (1–5 cm thick) of calcarenite and red quartzose calcarenite, and red quartz sand with laminae of quartz and carbonate layers < 1 cm thick	450 cm
lens of limestone 3 m thick and *circa* 20 m long, with large-scale cross-laminated, cream calcarenite composed of quartz sand, bioclasts, and ooids	300 cm
sharp contact with underlying mottled red sand of the Mowanjum Sand	

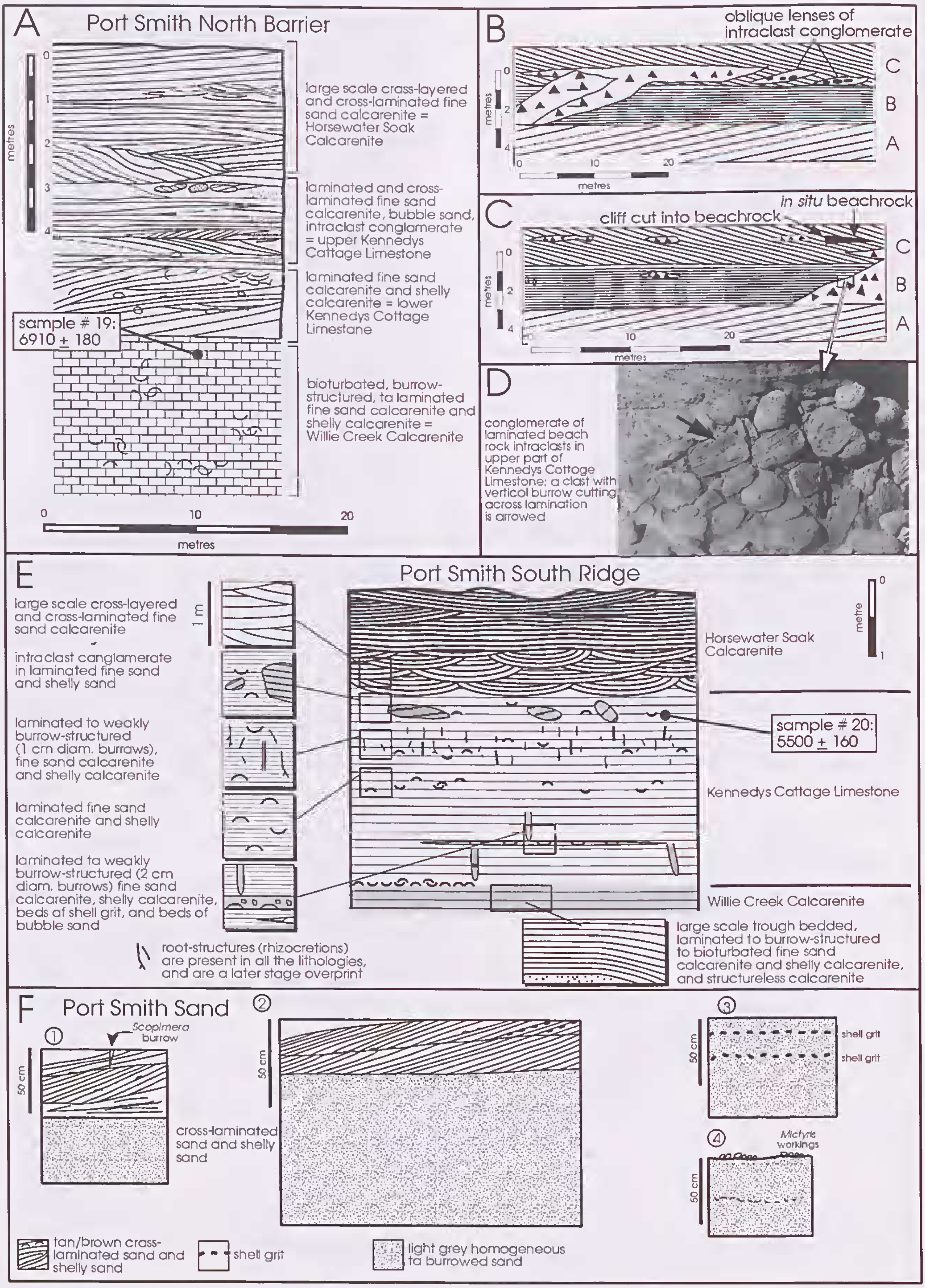
The base of the Formation at this section is located at *circa* 1 m above HAT.

Supplementary sections through the Barn Hill Formation showing limestone lenses, carbonate laminae, and the internal variation in lithology from red sand to carbonate sand expressed in lenses, beds, and laminae, are illustrated in Figures 17–19. The sharp contact of a calcarenite lens with underlying Mowanjum Sand is shown in Figure 19B. Close-up of a cross-laminated calcarenite lens showing interlayering of carbonate rich layers and red quartz sand rich layers is illustrated in Figure 19C.

Stratigraphic relationships:
The unit rests, with sharp contact, directly on Mowanjum Sand, or on a gravel bed of ironstone pebbles that rests on the Mowanjum Sand. The Formation is overlain with sharp contact, or gradational contact, by Church Hill Sand. The Formation also locally is overlain with sharp contact, or gradational contact, by Shoonta Hill Sand; if gradational, the transitional zone, some 1 m thick, is orange sand with a mixture of quartz sand and carbonate sand.

Fauna:
Molluscan shells occur in some horizons within the Formation. These are several metres above HAT, and appear to be middens. The shells in the Formation

◀ **Figure 21.** Port Smith area. A and B. Aerial photograph and map of stratigraphic units. C. Cliff exposure of the north barrier of Holocene calcarenite showing Horsewater Soak Calcarenite, Kennedys Cottage Limestone, and Willie Creek Calcarenite. D. Close-up of Kennedys Cottage Limestone showing lens of intraclast (beachrock) conglomerate, and laminated calcarenite. E. Laminated shelly calcarenite of the Kennedys Cottage Limestone. F. Cross section of Port Smith showing stratigraphy of the Holocene calcarenites, and the modern sedimentary units of Port Smith Sand and Sandfire calcilutite (HWSC = Horsewater Soak Calcarenite, UKCL = upper Kennedy Cottage Limestone, LKCL = lower Kennedy Cottage Limestone WCC = Willie Creek Calcarenite).


A Port Smith North Barrier
metres
0 1 2 3 4
large scale cross-layered and cross-laminated fine sand calcarenite = Horsewater Soak Calcarenite
laminated and cross-laminated fine sand calcarenite, bubble sand, intraclast conglomerate = upper Kennedys Cattage Limestone
laminated fine sand calcarenite and shelly calcarenite = lower Kennedys Cottage Limestone
sample # 19: 6910 ± 180
bioturbated, burrow-structured, to laminated fine sand calcarenite and shelly calcarenite = Willie Creek Calcarenite
0 10 20
metres
B
oblique lenses of intraclast conglomerate
C B A
metres
0 10 20
C
cliff cut into beachrock
in situ beachrock
C B A
metres
D
conglomerate of laminated beach rock intraclasts in upper part of Kennedys Cottage Limestone; a clast with vertical burrow cutting across lamination is arrowed
E
Port Smith South Ridge
large scale cross-layered and cross-laminated fine sand calcarenite
1 m
intraclast conglomerate in laminated fine sand and shelly sand
laminated to weakly burrow-structured (1 cm diam. burrows), fine sand calcarenite and shelly calcarenite
laminated fine sand calcarenite and shelly calcarenite
laminated to weakly burrow-structured (2 cm diam. burrows) fine sand calcarenite, shelly calcarenite, beds of shell grit, and beds of bubble sand
root-structures (rhizocretions) are present in all the lithologies, and are a later stage overprint
Horsewater Soak Calcarenite
metre
0 1
sample # 20: 5500 ± 160
Kennedys Cottage Limestone
Willie Creek Calcarenite
large scale trough bedded, laminated to burrow-structured to bioturbated fine sand calcarenite and shelly calcarenite, and structureless calcarenite
F Port Smith Sand
① ② ③ ④
Scopimera burrow
50 cm
cross-laminated sand and shelly sand
shell grit
shell grit
Mictyris workings
tan/brown cross-laminated sand and shelly sand
shell grit
light grey homogeneous to burrowed sand

include: *Anadara granosa, Modiolus auriculatus, Modiolus micropterus, Modiolus* cf. *trailii*, and *Saccostrea cucullata*. The shells comprise an allochthonous thanatocoenosis.

Age:
Radiocarbon dating of shells and calcarenite within the Formation places it in the Holocene (Table 6). A whole-of-calcarenite sample for radiocarbon analysis returned an age of 2740 ± 120 yrs BP (Figure 19B). Shells of *Saccostrea cucullata* from under a limestone lens returned an age of 900 ± 100 yrs BP (Figure 19C).

Discussion:
The Barn Hill Formation is a distinctive unit formed where the Pleistocene Mowanjum Sand crops out and interacts with coastal processes. Red sand has been remobilised along the coast from the Mowanjum Sand to form Holocene red quartz sand dunes. The red quartz sand is mixed as laminae with carbonate enriched sand derived from the coast to form distinctive carbonate layers (carbonate sand beds and laminae, and carbonate enriched quartz sand laminae). Carbonate-rich sand dunes encroach from the coast to form mounds, which when indurated by early diagenetic cementation, and buried by red sand, form limestone lenses.

Church Hill Sand

Definition and characteristics:
The Church Hill Sand is the name proposed for the mainly structureless but locally laminated to cross-laminated red quartz sand formed as a shoe-string deposit to lensoid deposit underlying supratidal dunes along the Canning Coast.

Derivation of Name:
After Church Hill, latitude/longitude coordinates 18° 21' 51" S, 122° 03' 52" E, Lagrange 1:250,000 Topographical Sheet.

Type section (Type locality):
Sand dunes near coast adjoining Church Hill, latitude/ longitude coordinates 18° 21' 51" S, 122° 02' 30" E, Lagrange 1:250,000 Topographical Sheet.

Distribution:
The unit is widespread along the Canning Coast as a semi-continuous to scattered shoe-string to lensoid deposit.

Thickness and geometry:
Where exposed along the coast, the Formation is usually 2–3 m thick, but has been recorded as up to 4 m thick. Regionally, the unit will appear as discontinuous shoe-string and lensoid deposits, individually, some tens of metres to several hundred of metres long, but only up to 100 m wide and 2–4 m thick.

Lithology:
In general, a red quartz sand, mainly structureless, but locally with lamination and cross-lamination.

The type section consists of:

Description	Thickness
structureless red quartz sand	400 cm
sharp contact with mottled red sand of the Mowanjum Sand	

The top of this section is the modern ground surface. The base of the Formation at this section is located several metres above HAT.

Stratigraphic relationships:
The unit rests, with sharp to gradational contact, on Barn Hill Formation. Locally it rests with sharp contact directly on Mowanjum Sand. The Formation is overlain with sharp contact, or gradational contact, by Shoonta Hill Sand; if gradational, the transitional zone, some 1 m thick, is orange sand with a mixture of quartz sand and carbonate sand.

Fauna:
No fauna has been recorded within the Formation.

Age:
The Formation overlies the Barn Hill Formation, which has been dated as Holocene, and hence the age of the Church Hill Sand also is Holocene.

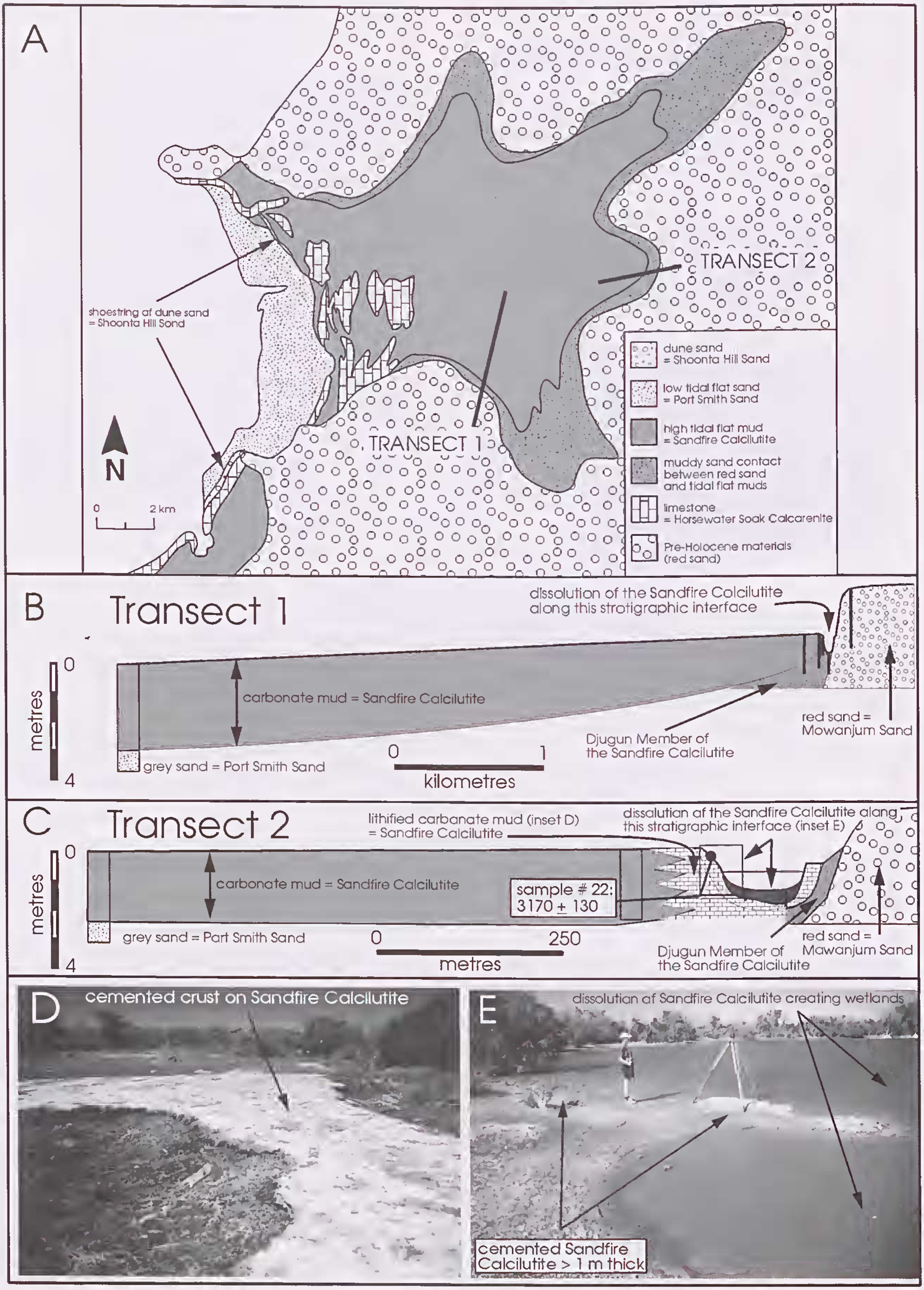
Discussion:
The Church Hill Sand is a distinctive unit formed where red sand is remobilised along the coast from the Mowanjum Sand where the latter is exposed along the coast.

Horsewater Soak Calcarenite

Definition and characteristics:
The Horsewater Soak Calcarenite is a cross-laminated and cross-bedded aeolian limestone (a fine to medium sand-sized bioclastic and quartzose, and locally oolitic calcarenite); it is generally a shoe-string deposit formed initially as mid-Holocene supratidal dunes along the Canning Coast, and later lithified.

Derivation of Name:
After Horsewater Soak, latitude/longitude coordinates 18° 21' 51" S, 122° 03' 52" E, Broome 1:250,000 Topographical Sheet.

◀ **Figure 22.** Details of stratigraphy of various units in the Port Smith area. A. Details of lithology in the Horsewater Soak Calcarenite, Kennedys Cottage Limestone, and Willie Creek Calcarenite exposed in cliffs of the north barrier. B–D. Details of intraclast conglomerate and beachrock in the Kennedys Cottage Limestone. E. Details of lithology in the Horsewater Soak Calcarenite, Kennedys Cottage Limestone, and Willie Creek Calcarenite exposed in cliffs of the south ridge. F. Stratigraphic details of the Port Smith Sand (the type section).


A
shoestring of dune sand = Shoonta Hill Sand
TRANSECT 1
TRANSECT 2
N
0 2 km
dune sand = Shoonta Hill Sand
low tidal flat sand = Port Smith Sand
high tidal flat mud = Sandfire Calcilutite
muddy sand contact between red sand and tidal flat muds
limestone = Horsewater Soak Calcarenite
Pre-Holocene materials (red sand)
B
Transect 1
dissolution of the Sandfire Calcilutite along this stratigraphic interface
metres
0
4
carbonate mud = Sandfire Calcilutite
grey sand = Port Smith Sand
0
1
kilometres
Djugun Member of the Sandfire Calcilutite
red sand = Mowanjum Sand
C
Transect 2
lithified carbonate mud (inset D) = Sandfire Calcilutite
dissolution of the Sandfire Calcilutite along this stratigraphic interface (inset E)
metres
0
4
carbonate mud = Sandfire Calcilutite
sample # 22: 3170 ± 130
grey sand = Port Smith Sand
0
250
metres
Djugun Member of the Sandfire Calcilutite
red sand = Mowanjum Sand
D
cemented crust on Sandfire Calcilutite
E
dissolution of Sandfire Calcilutite creating wetlands
cemented Sandfire Calcilutite > 1 m thick

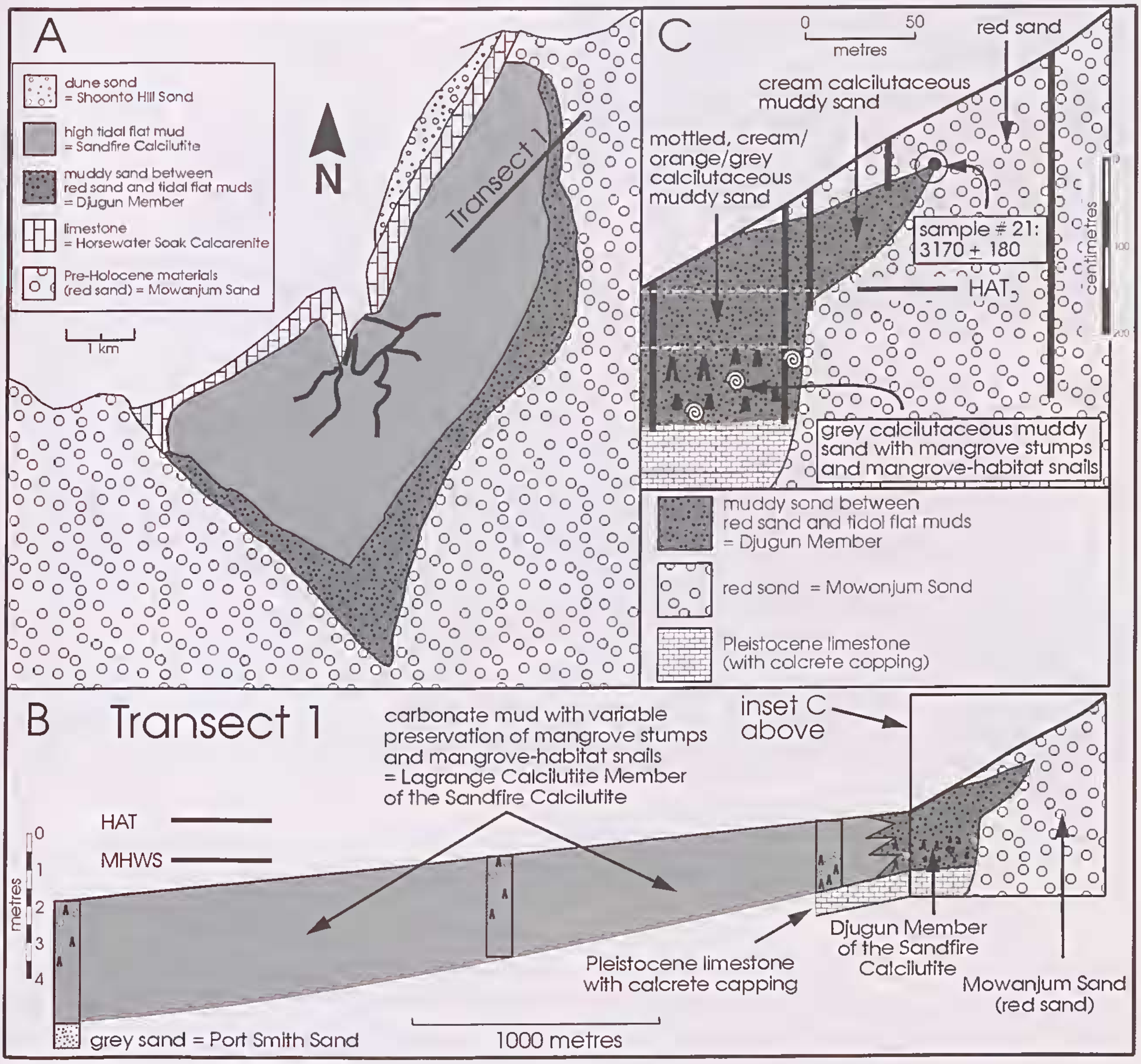


Figure 24. Cowan Creek area. A. Map of stratigraphic units. B and C. Stratigraphic profiles determined by augering showing relationship of Sandfire Calcilutite to Mowanjum Sand, and the occurrence of the Djugun Member between the Sandfire Calcilutite and Mowanjum Sand.

Type section (Type locality):

Cliff exposure on shores of Willie Creek, near Horsewater Soak, latitude/longitude coordinates 17° 46' 06" S, 122° 12' 54" E, Broome 1:250,000 Topographical Sheet. Horsewater Soak itself occurs as a wetland on the surface of the Formation near the type section.

Distribution:

The unit is widespread along the Canning Coast as a semi-continuous to scattered shoe-string to lensoid deposit.

Thickness and geometry:

Where exposed along the coast the Formation is generally 2 m to 3 m thick, but has been recorded as up to 5.5 m thick. Regionally, the unit will appear as discontinuous shoe-string and lensoid deposits, individually, some tens of metres to several hundred of metres long but only up to 100 m wide and generally 2–3 m thick.

◀ **Figure 23.** Lagrange area. A Map of stratigraphic units. B & C. Stratigraphic profiles determined by augering and by cliff exposures showing relationship of the Sandfire Calcilutite to Mowanjum Sand, the occurrence of the Djugun Member between the Sandfire Calcilutite and Mowanjum Sand, and the cementation of Sandfire Calcilutite along the zone of freshwater discharge along the interface between Sandfire Calcilutite and Mowanjum Sand. D. Cemented crust on the Sandfire Calcilutite. The top of the Sandfire Calcilutite here is located above the level of its modern upper depositional surface. E. Photograph of the cemented calcilutite from Transect 2. The Sandfire Calcilutite here also is located above the level of its modern upper depositional surface.

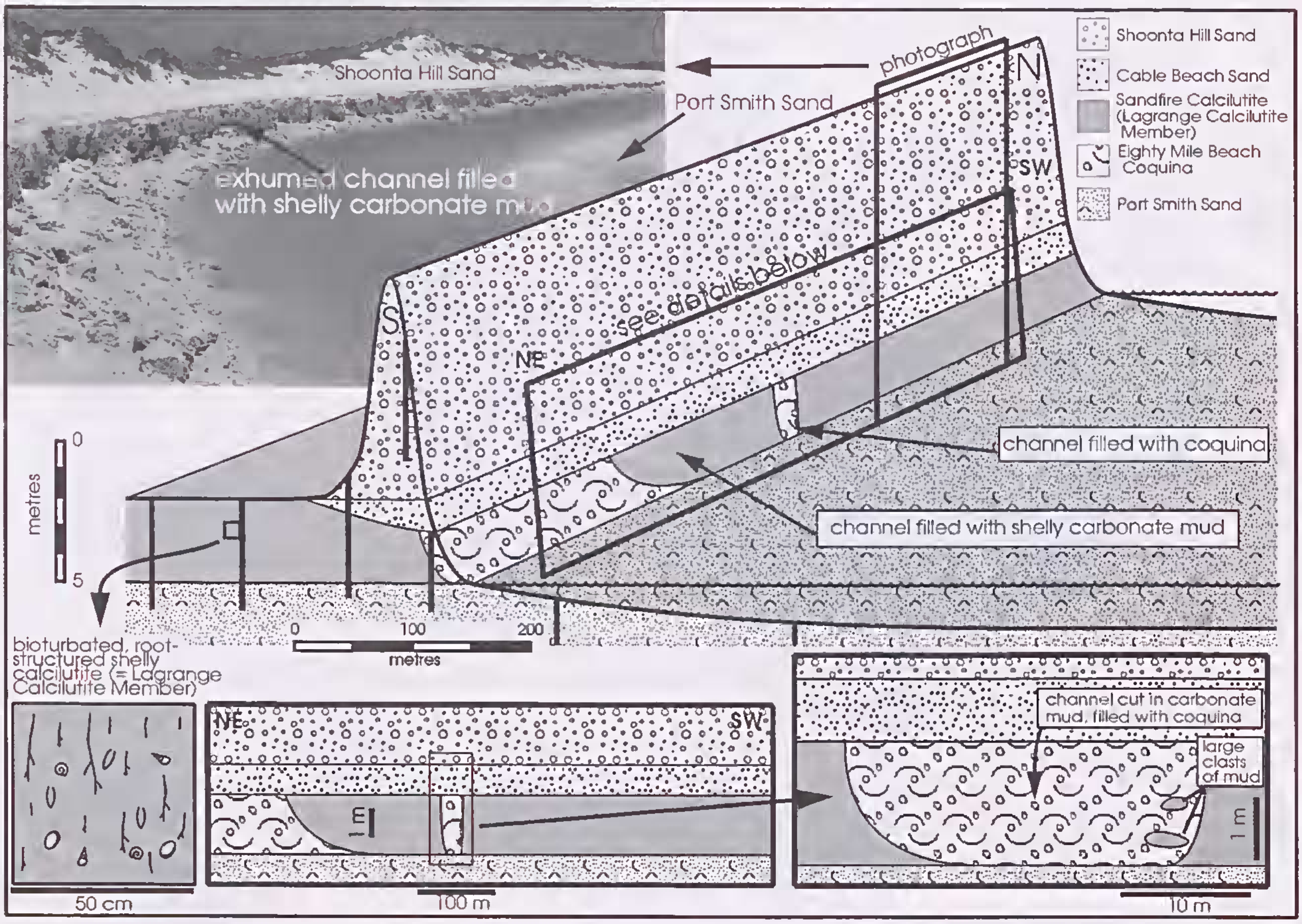


Figure 25. Northern Eighty Mile Beach. Stratigraphy as determined by cliff exposures and by augering. A shoestring of Shoonta Hill Sand perched on Sandfire Calcilutite is exposed at the coast. Its seaward edge is truncated by an erosional interface on which is perched the Eighty Mile Beach Coquina. Channel-fills of shelly calcilutite and coquina are exposed in a cliff along the shore, illustrating complex history of channeling and channel filling.

Lithology:

A fine to medium sand-sized bioclastic and quartzose and locally oolitic calcarenite. The cementing agent is sparry calcite. The limestone is laminated, cross-laminated, cross-bedded, to large-scale festoon-bedded.

The type section consists of:

Description	Thickness
large-scale cross-bedded and cross-laminated cream fine-grained quartzose, bioclastic and sparsely oolitic calcarenite	350 cm
sharp contact with Kennedys Cottage Limestone	

The top of this section is the ground surface. The base of the Formation at this section is located at *circa* 2 m above HAT.

Stratigraphic relationships:

Generally, the Formation rests with sharp contact on the Kennedys Cottage Limestone. Locally, the Formation rests on Willie Creek Calcarenite (Figure 11B). The Formation is overlain by Shoonta Hill Sand. Where it is being eroded by aeolian action, the Formation is yielding sand to the Shoonta Hill Sand. The base of the Formation is located about 1.5 to 2 m above the base of its contemporary lithosome where the base of modern dune deposits are located today.

Fauna:

Locally, there are shell lag horizons in the lower part of the Formation, composed of *Donax faba*. These shell lags are only thin. The assemblage is an allochthonous partial biocoenosis.

Age:

There are no radiocarbon ages derived from this Formation, but ages of 5500 ± 160 yrs BP, 5590 ± 240 yrs BP and 6910 ± 180 yrs BP from underlying calcarenites demonstrate its Holocene age (Figures 12 and 22).

Discussion:

The Horsewater Soak Calcarenite is a distinctive limestone unit formed earlier during the Holocene as coastal dunes. Since then it has been cemented by sparry calcite.

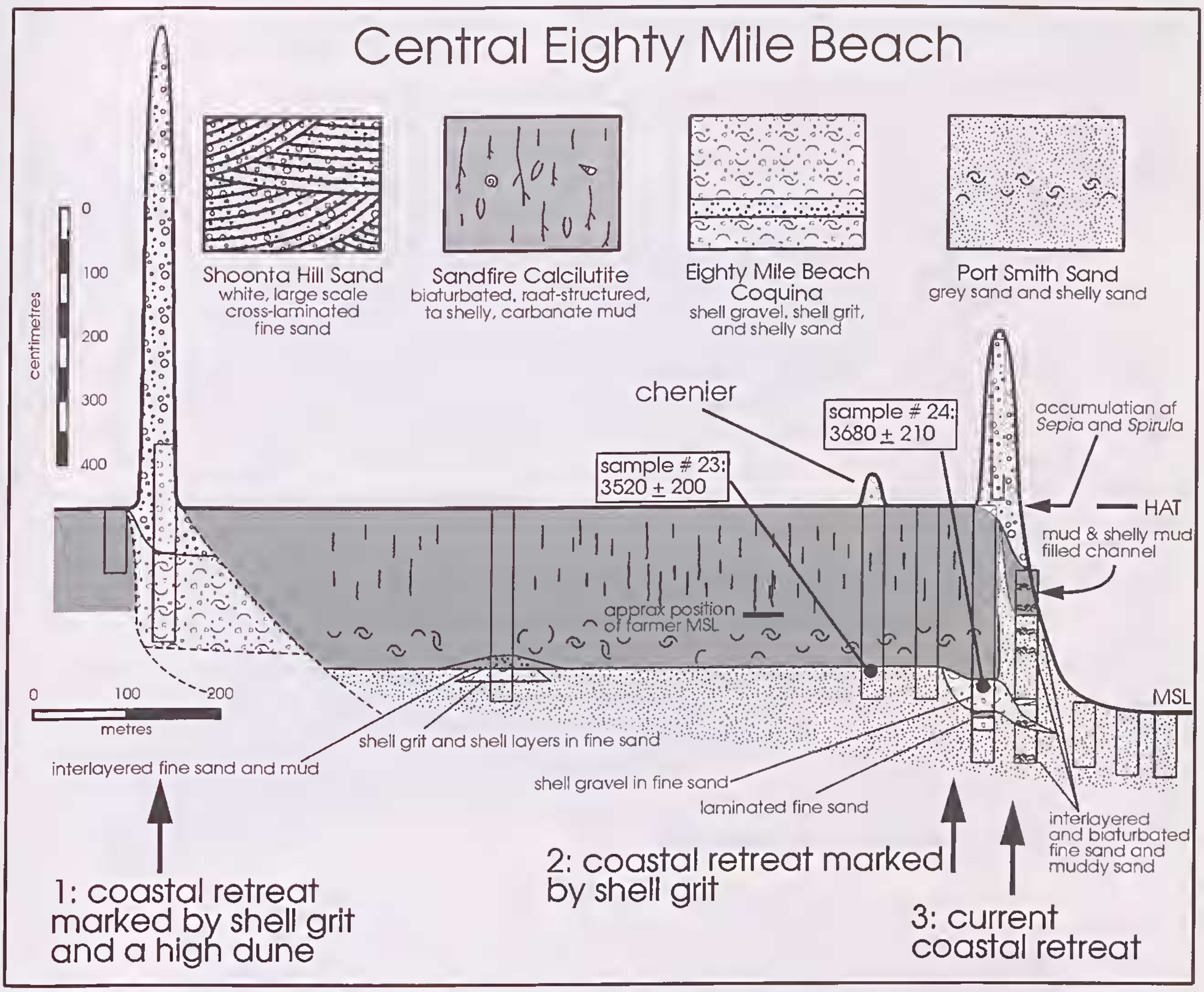


Figure 26. Central Eighty Mile Beach. Stratigraphy as determined by cliff exposures and by augering. At the shore, a shoestring of Shoonta Hill Sand is perched on an erosional interface cut into Sandfire Calcilutite. Earlier periods of coastal erosion and perching of dune sand or shell concentrates are evident in the transect. In this cross-section, the earliest phase of coastal retreat and development of a barrier dune and shoreface shell concentrate, for instance, is evident in the south part of the profile (arrow 1), and another phase of shore retreat and development of shell concentrate is evident *circa* 100 m south of the modern shore (arrow 2). Typical sedimentary-structural and lithological characteristics of the formations in this profile are also diagrammatically

Kennedys Cottage Limestone

Definition and characteristics:

The Kennedys Cottage Limestone is a laminated to cross-laminated calcarenite and shelly calcarenite with limestone intraclast conglomerate and breccia, and bubble structure ("bubble sand" structure); it is generally a ribbon deposit formed as mid-Holocene beach deposit along the Canning Coast.

Derivation of Name:

After Kennedys Cottage, latitude/longitude coordinates 17° 45' 18" S, 122° 12' 16" E, Broome 1:250,000 Topographical Sheet.

Type section (Type locality):

Cliff exposure on shores of Willie Creek, near Kennedys Cottage, latitude/longitude coordinates 17° 46' 06" S, 122° 12' 54" E, Broome 1:250,000 Topographical Sheet.

Distribution:

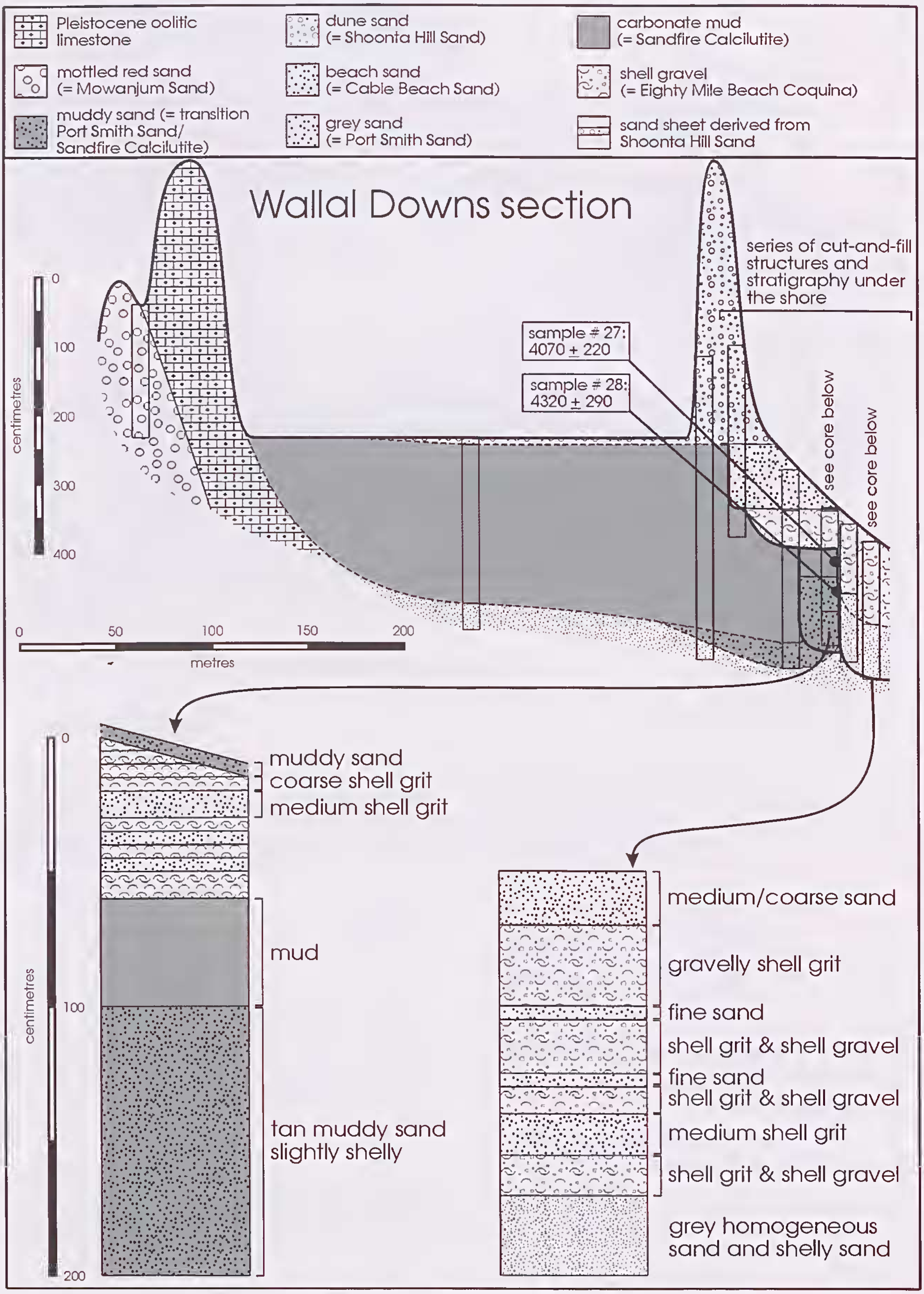
The unit is widespread along the Canning Coast as a semi-continuous to scattered ribbon deposit.

Thickness and geometry:

Where exposed along the coast, the Formation is 1.5–2.0 m thick, but has been recorded as up to 4 m thick. Regionally, the unit will appear as discontinuous ribbon deposit, individually, some tens of metres to several hundred of metres long, but only up to 100 m wide and generally up to 2 m thick.

Lithology:

A fine to medium to coarse sand-sized bioclastic, quartzose and sparsely oolitic calcarenite, with layers of shells, layers of bubble sand structures, and in its upper parts, lenses and wedges of limestone intraclast conglomerate and breccia, with clasts varying from cobble- and pebble-size to boulder-size. Sand grains are oolitically coated molluscs, quartz, foraminifera,



Pleistocene oolitic limestone
mottled red sand (= Mowanjum Sand)
muddy sand (= transition Port Smith Sand/ Sandfire Calcilutite)
dune sand (= Shoonta Hill Sand)
beach sand (= Cable Beach Sand)
grey sand (= Port Smith Sand)
carbonate mud (= Sandfire Calcilutite)
shell gravel (= Eighty Mile Beach Coquina)
sand sheet derived from Shoonta Hill Sand
Wallal Downs section
series of cut-and-fill structures and stratigraphy under the shore
sample # 27: 4070 ± 220
sample # 28: 4320 ± 290
see core below
see core below
centimetres
0
100
200
300
400
0
50
100
150
200
metres
muddy sand
coarse shell grit
medium shell grit
mud
tan muddy sand slightly shelly
centimetres
0
100
200
medium/coarse sand
gravelly shell grit
fine sand
shell grit & shell gravel
fine sand
shell grit & shell gravel
medium shell grit
shell grit & shell gravel
grey homogeneous sand and shelly sand

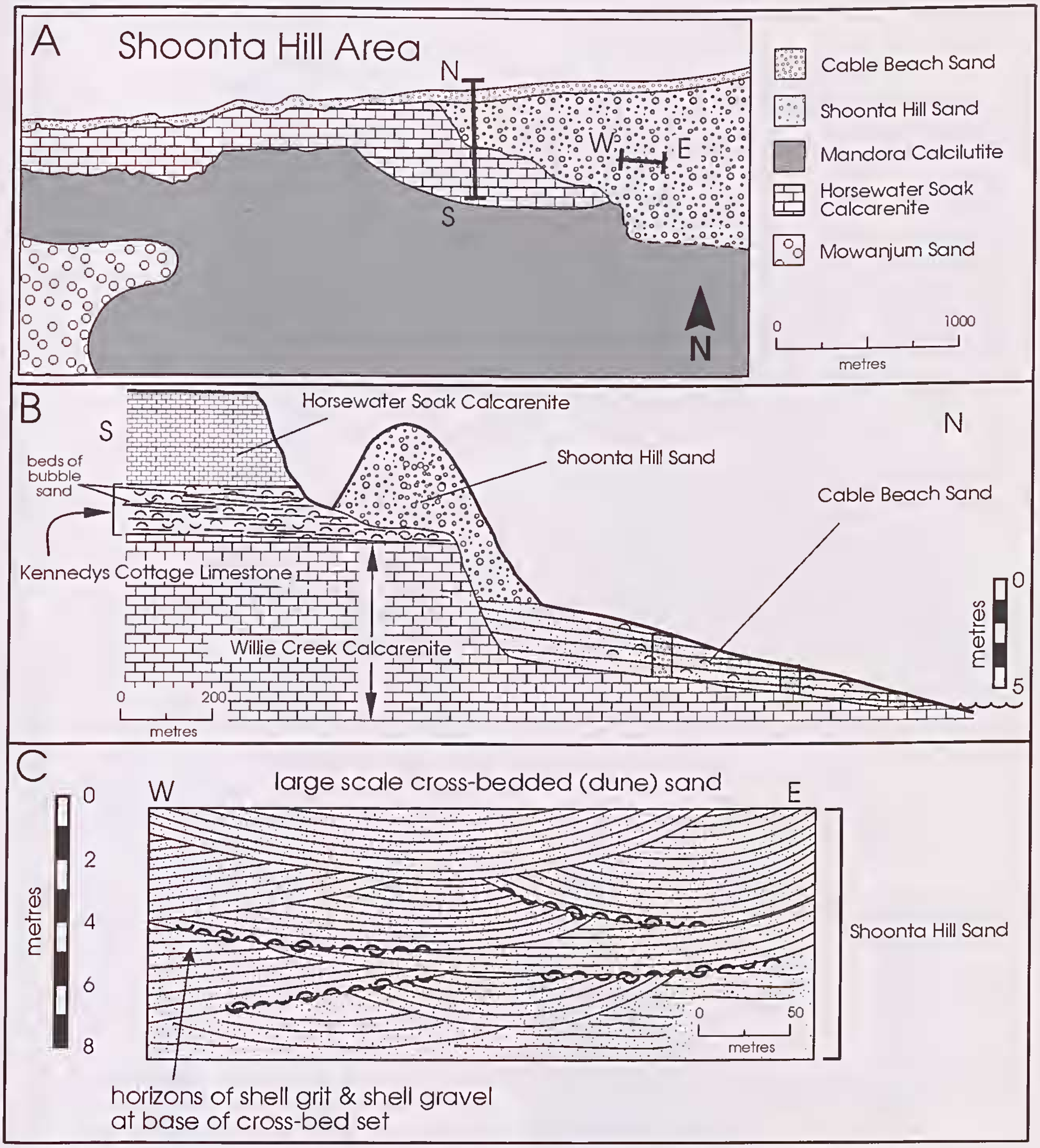
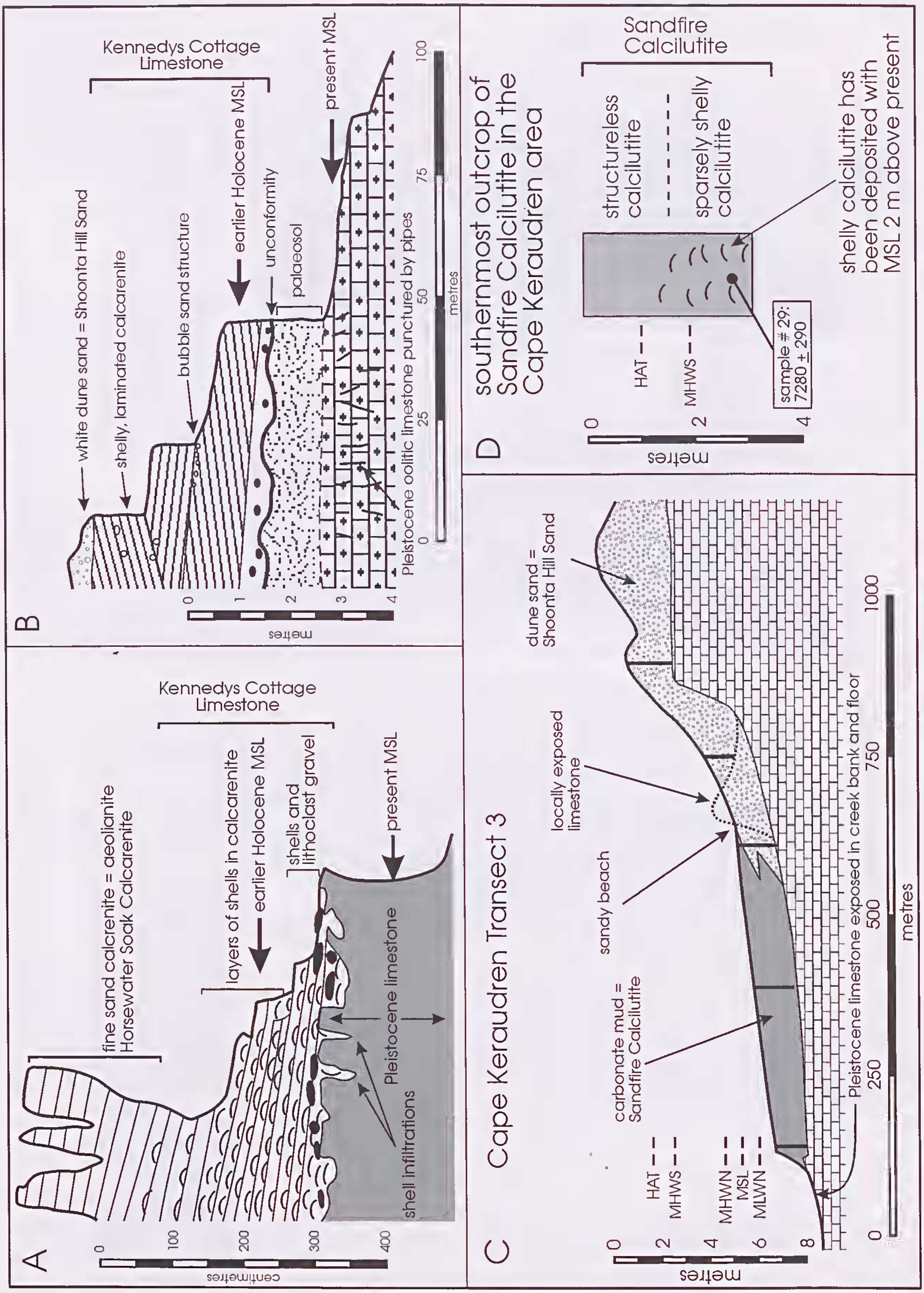


Figure 28. Shoonta Hill area. A. Map of stratigraphic units. B. Cross-section based on cliff exposures and cores illustrating the disposition and inter-relationships of the Holocene stratigraphic units: Willie Creek calcarenite, Kennedys Cottage Limestone, Horsewater Soak Calcarenite, Cable Beach Sand, and Shoonta Hill Sand. C. A cliff exposure, eroded by wind action, the type section of Shoonta Hill Sand, shows internal stratigraphy of the formation: large scale cross-bedded, fine-grained sand with horizons of shell grit and shell gravel developed as former wind-lag deposits.

◀ **Figure 27.** Southern Eighty Mile Beach. Stratigraphy as determined by cliff exposures and by augering. At the shore, a shoaling sequence of Eighty Mile Beach Coquina, Cable Beach Sand, capped by a shoestring of Shoonta Hill Sand are perched on an erosional interface cut into Sandfire Calcilutite. The Holocene sequence of Sandfire Calcilutite, Eighty Mile Beach Coquina, Cable Beach Sand and Shoonta Hill Sand abuts a ridge of Pleistocene oolitic limestone, which in turn abuts the Pleistocene Mowanjum Sand.


A
fine sand calcrenite = aeolianite
Horsewater Soak Calcarenite
Kennedys Cottage Limestone
layers of shells in calcarenite
earlier Holocene MSL
shells and lithoclast gravel
present MSL
Pleistocene limestone
shell infiltrations
0
100
200
300
400
centimetres
B
white dune sand = Shoonta Hill Sand
shelly, laminated calcarenite
bubble sand structure
earlier Holocene MSL
unconformity
palaeosol
Kennedys Cottage Limestone
present MSL
Pleistocene oolitic limestone punctured by pipes
0
25
50
75
100
metres
0
1
2
3
4
metres
C
Cape Keraudren Transect 3
HAT
MHWS
MHWN
MSL
MLWN
carbonate mud = Sandfire Calcilutite
sandy beach
locally exposed limestone
dune sand = Shoonta Hill Sand
Pleistocene limestone exposed in creek bank and floor
0
250
500
750
1000
metres
0
2
4
6
8
metres
D
southernmost outcrop of Sandfire Calcilutite in the Cape Keraudren area
Sandfire Calcilutite
structureless calcilutite
sparsely shelly calcilutite
HAT
MHWS
sample # 29:
7280 ± 290
shelly calcilutite has been deposited with MSL 2 m above present
0
2
4
metres

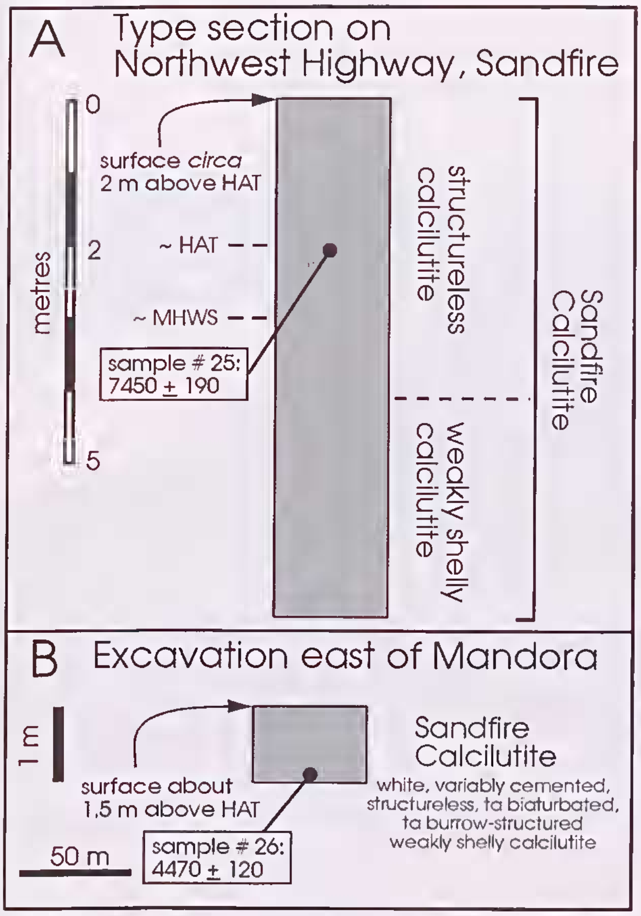


Figure 30. Miscellaneous locations for stratigraphy along the Canning Coast. A. Type location for the Sandfire Calcilutite along Northwest Highway. Site for sample collected for radiocarbon analysis shown. B. Sandfire Calcilutite exposed in excavation in the Mandora area. Site for sample collected for radiocarbon analysis shown.

intraclasts, and lithoclasts, and echinoderm fragments (Figure 7E). The cementing agent in the main body of the calcarenite is sparry calcite (Figure 7E). Locally, there is *in situ* beach rock.

The type section consists of:

Description	Thickness
aeolianite of Horsewater Soak Calcarenite	75 cm
laminated to low angle cross-laminated fine and medium calcarenite, with shell layers	
lens of conglomerate composed of cobble-sized laminated calcarenite intraclasts	50 cm
laminated to low angle cross-laminated fine and medium calcarenite, with scattered oriented shell and 5 cm thick layer of bubble sand structures	20 cm
laminated to low angle cross-laminated fine and medium calcarenite, with shell layers	50 cm
sharp contact with the underlying Willie Creek Calcarenite	

The base of the Formation at this section is located at *circa* 2 m above MHWS.

Stratigraphic relationships:
The Formation rests with sharp contact on the laminated, cross-laminated and bioturbated shelly Willie Creek Calcarenite. The Formation is overlain by Horsewater Soak Calcarenite.

Fauna:
The shell fauna includes the bivalves *Acrosterigma* cf. *fultoni, Anadara crebricostata, Anadara granosa, Anadara* sp., *Arca avellana, Asaphis violascens, Barbatia foliata, Callista impar, Donax faba, Donax* sp., *Dosinia* sp., *Fragum hemicardium, Gafrarium tumidum, Modiolus micropterus, Saccostrea cucullata,* and an unidentified Venerid, and the gastropod *Melo amphora.* The assemblage is an allochthonous thanatocoenosis.

Age:
Radiocarbon dating of shells within the Formation places it in the Holocene, *viz.*, 5500 ± 160 yrs BP and 5590 ± 240 yrs BP (Table 6, and Figures 12 and 22).

Discussion:
The Kennedys Cottage Limestone is a distinctive limestone unit formed earlier during the Holocene as a beach deposit. It has the sedimentary structures and interlayering of sediments typical of beaches. Bubble sand structure and *in situ* beach rock also are diagnostic. The limestone intraclast conglomerate and breccia are storm reworking of beach rock slabs. The sedimentary suite is located about 1.5 m to 2 m above its contemporary lithosome.

Willie Creek Calcarenite

Definition and characteristics:
The Willie Creek Calcarenite is bedded to large-scale festoon-bedded, laminated, burrow-structured to bioturbated calcarenite and shelly calcarenite; it is a ribbon deposit formed as mid- to low tidal sand and shelly sand during the mid-Holocene along the coastal zone of the Canning Coast.

Derivation of Name:
After Willie Creek, latitude/longitude coordinates 17° 45' 54" S, 122° 12' 56" E, Broome 1:250,000 Topographical Sheet.

Type section (Type locality):
Cliff exposure on shores of Willie Creek, latitude/longitude coordinates 17° 46' 07" S, 122° 12' 55" E, Broome 1:250,000 Topographical Sheet.

Distribution:
The unit is widespread along the Canning Coast as a semi-continuous to scattered ribbon- deposit.

◀ **Figure 29.** Cape Keraudren area. A & B. Stratigraphy of Holocene calcarenites and shelly calcarenites exposed in cliffs in the area. These calcarenites rest with unconformity on Pleistocene limestone, or locally on Pleistocene palaeosols that are developed on the Pleistocene limestone. C. Stratigraphic profile showing Sandfire Calcilutite in relation to Shoonta Hill Sand, both overlying limestone. D. Section exposed in excavation of the Sandfire Calcilutite, with location of sample collected for radiocarbon analysis.

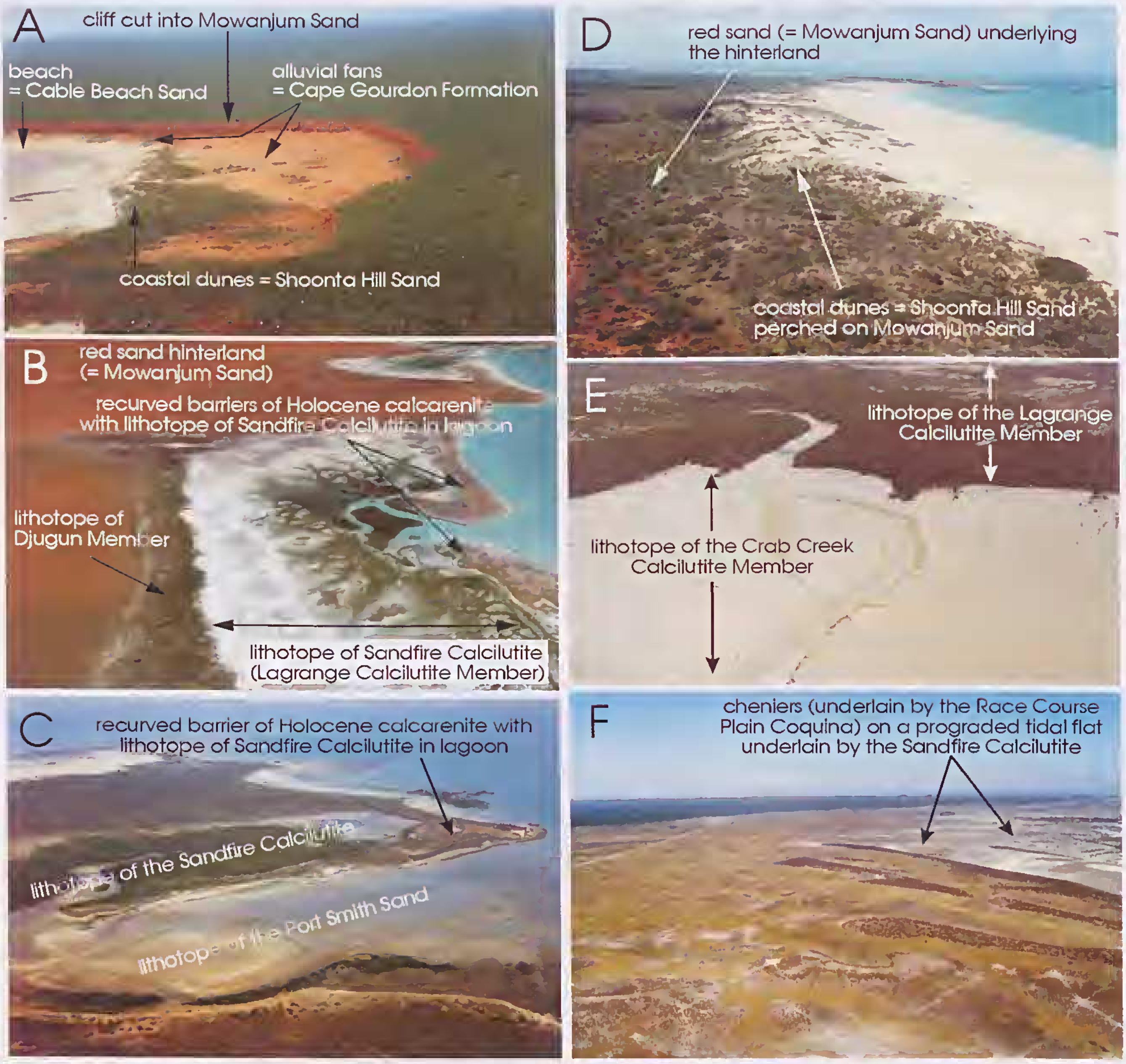


Figure 31. Oblique aerial photographs illustrating stratigraphic features and sedimentary lithotopes. A. Coastline near Cape Leveque showing eroding Mowanjum Sand with coastal alluvial fans (Cape Gourdon Formation), a small dune barrier (= Shoonta Hill Sand), and beach sand (= Cable Beach Sand). B. Cowan Creek showing red sand hinterland underlain by Mowanjum Sand, and Holocene calcarenite barriers (Horsewater Soak Calcarenite) barring the lagoon where mud of the Sandfire Calcilutite is accumulating; the zone of mixing between calcilutite and red sand is the lithotope of the Djugun Member. C. Southern entrance to Pender Bay showing Holocene calcarenite barrier (Horsewater Soak Calcarenite) protecting a lagoon where mud of the Sandfire Calcilutite is accumulating; lithotope of Port Smith Sand is in the protected zone of the embayment. D. Coast near Lagrange Bay showing coastal dunes (=Shoonta Hill Sand) perched on Mowanjum Sand. E. Crab Creek, northern Roebuck Bay, showing disposition of the lithotopes of Crab Creek Calcilutite Member and Lagrange Calcilutite Member. F. Race Course Plains, near Thangoo, showing cheniers (underlain by Race Course Plains Coquina) on a prograded tidal flat underlain by Sandfire Calcilutite.

Thickness and geometry:
Where exposed along the coast the Formation has been recorded 3–5 m thick, but can be up to 7 m thick. Regionally, the unit will appear as a discontinuous ribbon deposit, individually, some tens of metres to several hundred of metres long, but only up to 100 m wide and generally 3–5 m thick.

Lithology:
A fine to medium to coarse sand-sized bioclastic and quartzose calcarenite, with layers of shells. Sand grains are quartz, lithoclasts, intraclasts, molluscs fragments, and oolitically coated grains. The cementing agent is sparry calcite. It is burrow-structured to bioturbated to laminated and bedded.

The type section consists of:

Description	Thickness
indurated beach deposits of the Kennedys Cottage Limestone	
low-angle cross-layered to cross-bedded and laminated burrow-structured to bioturbated fine-grained to medium grained calcarenite and shelly calcarenite	300 cm
base not exposed	

The contact of the Formation with overlying Kennedys Cottage Limestone at this section is located at *circa* 2 m above the contemporary interface.

Stratigraphic relationships:
Mostly the Formation is overlain by the Kennedys Cottage Limestone, but locally it may be overlain directly with sharp contact by the Horsewater Soak Calcarenite (Figure 11B). Where cut by more recent channels, the Formation is overlain by channel-fills composed of Christine Point Clay and/or Sandfire Calcilutite. Where exposed, the Formation rests with sharp contact on pre-Holocene Formations such as Mowanjum Sand, or red ironstone gravel, or palaeosol developed on Pleistocene limestone.

Fauna:
The molluscan shell fauna includes the bivalves *Acrosterigma fultoni, Acrosterigma vlamingi, Anadara crebricostata, Anomalocardia squamosa, Barbatia coma, Barbatia foliata, Callista impar, Donax faba, Donax* cf. *faba, Dosinia scalaris, Gafrarium tumidum, Saccostrea cucullata, Semele jukesii, Tellina virgata,* an unidentified Cardiid, and an unidentified Venerid, and the gastropods *Conus* sp. and *Strombus campbelli.* The assemblage is an allochthonous thanatocoenosis.

Age:
Radiocarbon dating of shells within the Formation places it in the Holocene, *viz.*, 3060 ± 600 yrs BP and 6910 ± 180 yrs BP (Table 6, and Figures 11 and 22)

Discussion:
The Willie Creek Calcarenite is a distinctive limestone unit formed earlier during the Holocene as a low tidal sand and shelly sand deposit, with an abundant ichnofauna. It has the sedimentary structures and interlayering of sediments typical of low tidal sand flats.

Radiocarbon ages of the stratigraphic units

The current active depositional nature of many of the stratigraphic units indicates their Holocene age, but additionally, radiocarbon dates obtained from selected sites in the stratigraphic profiles, as shown in the illustrations, and to be described later, confirm the Holocene age for the units. All twenty nine samples of shell, carbonate mud, or mangrove wood submitted for radiocarbon analyses in this study yielded Holocene ages, with the oldest being 7450 ^{14}C yrs BP and the youngest 900 ^{14}C yrs BP. Table 6 presents a catalogue of the samples listing sample number (this paper) ordered from northern sites to southern sites, field code, laboratory code, Formation from where the sample was collected, the rationale for collection, and the results in terms of ^{13}C ‰ PDB, ^{14}C pMC ± 1σ, and age in ^{14}C yr BP ± 1σ>

The oldest Holocene deposits encountered in this study returned radiocarbon ages of 7450 ± 190 ^{14}C yrs BP, 7280 ± 290 ^{14}C yrs BP and 5070 ± 270 ^{14}C yrs BP for occurrences of Sandfire Calcilutite in stranded coastal plain inland sites, 6910 ± 180 ^{14}C yrs BP, 5590 ± 240 ^{14}C yrs BP and 5500 ± 160 ^{14}C yrs BP for the earlier Holocene calcarenite Formations of Willie Creek Calcarenite and Kennedys Cottage Limestone, and 5310 ± 260 ^{14}C yrs BP for a channel-fill deposit of the Christine Point Clay in the Beagle Bay area. The earlier Holocene calcarenite Formations ranged in age from 6910 ± 180 ^{14}C yrs BP to 3060 ± 600 ^{14}C yrs BP for the Willie Creek Calcarenite, and returned ages of 5590 ± 240 ^{14}C yrs BP and 5500 ± 160 ^{14}C yrs BP for the Kennedys Cottage Limestone, indicating that the sedimentation that resulted in the formation of these Holocene calcarenites occurred *circa* 7000 yrs BP to *circa* 3000 yrs BP.

The radiocarbon dates from the Sandfire Calcilutite returned a range of ages, depending on location from the present coast and on its position relative to present sea level; these are 1390 ± 170 ^{14}C yrs BP, 3170 ± 130 ^{14}C yrs BP, 3415 ± 260 ^{14}C yrs BP, 4070 ± 220 ^{14}C yrs BP and 4470 ± 120 ^{14}C yrs BP. The uppermost part of the Djugun Member of the Sandfire Calcilutite, located 2 m above the highest tide, returned an age of 3170 ± 180 ^{14}C yrs BP showing that relative sea level was still elevated *circa* 3000 yrs BP (see later).

The Shoonta Hill Sand and the Cable Beach Sand, where sampled, are relatively young Formations, returning ages of 1190 ± 170 ^{14}C yrs BP and 2440 ± 190 ^{14}C yrs BP, and 1090 ± 160 ^{14}C yrs BP and 2100 ± 180 ^{14}C yrs BP, respectively. They appear to be products of sedimentation with sea level at its present position (see later). Where sampled, under the Sandfire Calcilutite that underlies prograded plains, the Port Smith Sand returned ages of 3520 ± 200 ^{14}C yrs BP, 3680 ± 210 ^{14}C yrs BP, and 4320 ± 220 ^{14}C yrs BP.

Radiocarbon dates from the Barn Hill Formation show ages that range from 2740 ± 120 ^{14}C yrs BP to 900 ± 100 ^{14}C yrs BP, with the shell midden under a limestone lens returning the age of 900 ± 100 ^{14}C yrs BP.

The Race Course Plains Coquina, being a mixture of storm/wave deposited shells and middens, returned a variety of ages depending on mode of shell accumulation and on location from the coast. Most of the samples from this Formation were of middens. The ages returned from

Table 6

Catalogue of samples submitted for radiocarbon analyses listing sample number (this paper) listed 1–29 in order from northern sites to southern sites, field code, laboratory code and material used, Formation from where the sample was collected, the rationale for sample collection, and the results in terms of ^{13}C ‰ PDB, ^{14}C pMC ± 1σ< and age in ^{14}C yr BP ± 1σ. (NA = not available)

Sample #	Field sample code and material	Laboratory Code	Formation PDB	Rationale for sample collection	^{13}C ‰	^{14}C pMC ± 1σ	^{14}C yrs BP ± 1σ
1	94-BB-Transect bb-CPC top: wood	DA 755	Christine Point Clay	to determine age of the Christine Point Clay and overlying age of the Sandfire Calcilutite in Camp Inlet	-25.4	79.9 ± 1.8	1800 ± 190
2	94-BB-Transect bb-CPC base: wood	DA 754	Christine Point Clay	to determine age of the base of the Christine Point Clay in Camp Inlet	-26.0	73.8 ± 1.7	2470 ± 200-190
2	94-BB-Transect bb-CPC base: wood (repeat)	DA 853	Christine Point Clay	to determine age of the base of the Christine Point Clay in Camp Inlet	-26.0	71.9 ± 1.7	2660 ± 200
2	94-BB-Transect bb-CPC base: wood (AMS)	OZC 242	Christine Point Clay	to determine age of the base of the Christine Point Clay in Camp Inlet	-26.0	73.9 ± 0.5	2430 ± 50
3	94-BB-b-ii-soil-*Anadara*: shell	DA 737	Shoonta Hill Sand	to determine age of the soil and associated shell midden in the dune sands in Camp Inlet	-1.3	73.8 ± 1.7	2440 ± 190
4	94-BB-4-CPC-grey mud: wood	DA 756	Christine Point Clay	to determine age of the Christine Point Clay in Beagle Bay	-22.8	51.7 ± 1.6	5310 ± 260-250
5	94-BB-"WCC"-2b: shell	DA 721	Willie Creek Calcarenite	to determine age of the Willie Creek Calcarenite in Camp Inlet; and for determining date of former MSL	1.8	68.4 ± 4.9	3060 ± 600-560
6	94-WC-2: shell	DA 716	Kennedys Cottage Limestone	to determine age of the Kennedys Cottage Limestone in Willie Creek; and for determining date of former MSL	0.0	49.9 ± 1.5	5590 ± 240
7	Broome-95-CBN-3-150 cm: shell	DA 722	Cable Beach Sand	to determine age of the prograded Cable Beach Sand at the Type Location at Cable Beach; and for determining date of former MSL	2.0	87.3 ± 1.8	1090 ± 160
8	Broome-95-CBN-5-270 cm: shell	DA 723	Cable Beach Sand	to determine age of the prograded Cable Beach Sand at the Type Location at Cable Beach; and for determining date of former MSL	2.0	77.0 ± 1.7	2100 ± 180
9	Sample # 1 *Pitar* shell, Ollies Bar mud: shell	GX-9220	Sandfire Calcilutite	to determine age of the upper part of the Sandfire Calcilutite under a spit/dune at Dampier Creek; and for determining date of former MSL	-7.5	NA	3415 ± 260

10	Sample # 2 *Anadara* shells, Ollies Bar Lst: shell	GX-9221	Race Course Plains Coquina	to determine age of middens in the upper part of the shelly sand bar emanating from the headland at the entrance to Dampier Creek	-0.4	NA	3625 ± 260
11	Sample # 3 Oyster shells, RB-1 Roebuck: shell	GX-9222	Race Course Plains Coquina	to determine age of the Race Course Plains Coquina in Roebuck Plains	+1.8	NA	2350 ± 225
12	Sample # 4 *Anadara* shells, RB-1 Roebuck: shell	GX-9223	Race Course Plains Coquina	to determine age of the Race Course Plains Coquina in Roebuck Plains	+0.2	NA	1285 ± 150
13	Roebuck Plains M.T. level (CO_3): carbonate mud	AMS	Sandfire Calcilutite	to determine age of the lower part of the Sandfire Calcilutite in the middle of the prograded Roebuck Plains	1.2	53.2 ± 1.8	5070 ± 270
14	94-Th (Thangoo)-BD-dune slope: midden shell	DA 733	Shoonta Hill Sand	to determine age of midden shells on the slope of a dune	-0.8	86.2 ± 1.8	1190 ± 170
15	94-Th (Thangoo)-BD-Mid- Sa: shell	DA 769	Sandfire Calcilutite	to determine age of shells in the upper part of a prograded plain underlain by Sandfire Calcilutite	0.1	84.1 ± 1.8	1390 ± 170
16	Sample # 5 *Anadara* shells, Thangoo: shell	GX-9224	Race Course Plains Coquina	to determine age of the Race Course Plains Coquina in the Thangoo area	+0.2	NA	1510 ± 210
17	BH-Holocene Dune	CS 1613	Barn Hill Formation	to determine age of a limestone lens in the Barn Hill Formation in the Barn Hill area	3.4	71.1 ± 1.2	2740 ± 120
18	BH-under dune limestone lens: oyster shell	CS 1614	Barn Hill Formation	to determine age of a shell midden under a limestone lens in the Barn Hill Formation in the Barn Hill area	0.3	89.4 ± 1.3	900 ± 100
19	Port Smith New Barrier (PS-NB 4m): shell	CS 1615	Willie Creek Calcarenite	to determine age of the Kennedys Cottage Limestone in the Port Smith area; and for determining date of former MSL	-0.9	42.3 ± 1.0	6910 ± 180
20	Port Smith Old Barrier (PS-= OB-l): shell	CS 1616	Kennedys Cottage Limestone	to determine age of a Willie Creek Calcarenite in the Port Smith area; and for determining date of former MSL	0.9	50.4 ± 1.1	5500 ± 160
21	1999 #5 GSD-5 (Termite CO_3): carbonate mud	CS 2412 / ANU 24204	Djugun Member	to determine age of the Sandfire Calcilutite where it onlaps Mowanjum Sand with a former MSL 1.5 m higher than present	-0.1	NA	3170 ± 180
22	1999 #6 GSD-01 (CCC): carbonate mud	CS 2413	Sandfire Calcilutite	to determine age of the upper surface of Sandfire Calcilutite where it occurs 1.5 m above HAT	-5.4	NA	3170 ± 130
23	95-Mandora-I-250 cm: shell	DA 734	Port Smith Sand	to determine age of the Port Smith Sand where it occurs 250 cm deep under a prograded plain; and for determining date of former MSL	1.4	64.5 ± 1.6	3520 ± 200

Table 6 (cont.)

Sample #	Field sample code and material	Laboratory Code	Formation PDB	Rationale for sample collection	^{13}C ‰	^{14}C pMC ± 1σ	^{14}C yrs BP ± 1σ
24	95-Mandora-G-280 cm: shell	DA 735	Eighty Mile Beach Coquina	to determine age of the Eighty Mile Beach Coquina where occurs 280 cm deep under a prograded plain	1.6	63.2 ± 1.6	3680 ± 210
25	1999 #7 Samphire 200 cm depth (at Sandfire): carbonate mud	CS 2414	Sandfire Calcilutite	to determine age of the Sandfire Calcilutite 2 m below the surface at the Type Section where it occurs some 20 km inland from the present coast; and for determining date of former MSL	3.4	NA	7450 ± 190
26	Mandora – Samphire calcilutite (CO_3): carbonate mud	CS 299	Sandfire Calcilutite	to determine age of the Sandfire Calcilutite 1 m below the surface where it occurs some 15 km inland from the present coast; and for determining date of former MSL	1.0	57.3 ± 0.9	4470 ± 120
27	80 mi beach- L.T.: carbonate mud	DA 767	Sandfire Calcilutite	to determine age of the Sandfire Calcilutite where it is exposed along the toe of the beach of a retreating coast	1.8	60.2 ± 1.6	4070 ± 220
28	80 mi beach : shell in sand under mud: shell	DA 768	Port Smith Sand	to determine age of the Port Smith Sand that underlies the Sandfire Calcilutite (the latter being exposed along the toe of the beach of a retreating coast)	1.3	58.4 ± 1.6	4320 ± 220
29	94-CK-excavation 2.5 m deep: shell	DA 736	Crab Creek Calcilutite Member	to determine age of the Sandfire Calcilutite 2.5 m below the surface where it occurs some 3 km inland from its present depositional regime	0.7	40.4 ± 1.5	7280 ± 290

shell from the Race Course Plains Coquina are 1285 ± 150 ^{14}C yrs BP, 2290 ± 180 ^{14}C yrs BP, 1510 ± 210 ^{14}C yrs BP, 2350 ± 225 ^{14}C yrs BP and 3625 ± 260 ^{14}C yrs BP.

The Eighty Mile Beach Coquina, a unit formed as a result of coastal retreat, essentially is a lag concentrate of molluscan shell and as such will represent accumulation of material reworked from older Formations. Only one radiocarbon date was obtained from this Formation, and this was 3680 ± 210 ^{14}C yrs BP.

Not all dates reflect progressive younging of the sequences shorewards towards the coast. Depending on whether the coast is prograding or retreating, the most coastally located material may be the youngest, or may be exposed older material.

While there has been a range of ages returned from Holocene units that are stranded under the prograded coastal plain, it is re-emphasised here that the Shoonta Hill Sand, Sandfire Calcilutite, Cable Beach Sand, Port Smith Sand, Eighty Mile Beach Coquina, Barn Hill Formation, and Church Hill Sand are contemporary units, still accumulating and accreting in the modern environments. The radiocarbon ages, however, provide a measure of their longevity as Holocene units.

A summary of the ages returned in relation to the stratigraphic units is provided in Table 7.

Key stratigraphic relationships

As noted earlier in this paper, the Holocene units unconformably rest on a variety of older systems. Along much of the coast, they rest on Pleistocene red dune sand, referable to the Mowanjum Sand (Semeniuk 1980). However, the Holocene units also rest on bedrock and lateritic Formations of Mesozoic to Quaternary age, and various Pleistocene limestones. Where Holocene sediments rest on unconsolidated material such as red sand, the unconformity is often blurred by bioturbation. Elsewhere, the contact commonly is sharp. In the Camp Inlet and Beagle Bay area, the Sandfire Calcilutite unconformably rests on a mangrove tidal flat terrigenous clay unit, the Christine Point Clay, described originally in the King Sound area (Semeniuk 1980).

In terms of Holocene stratigraphy, the three limestone units, *viz.*, the Willie Creek Calcarenite, the Kennedys Cottage Limestone, and the Horsewater Soak Calcarenite, and the inland occurrences of Sandfire Calcilutite, are the oldest Holocene Formations in the region. In terms of more contemporary units, the Port Smith Sand is a basal Formation that underlies all unconsolidated later Holocene units. The Sandfire Calcilutite, Cable Beach Sand, and Eighty Mile Beach Coquina, located in the mid- to high-tidal range, are laterally equivalent units representing a change from low energy progradational to high energy progradational to high energy dominantly erosional. The Shoonta Hill Sand generally caps those sequences formed under high energy conditions, but also forms a unit overlying Sandfire Calcilutite where the coast is markedly retrograding and dunes are coastally ingressing. The Race Course Plains Coquina occurs as a shoe-string deposit embedded in, or resting on the Sandfire Calcilutite. The Barn Hill Formation, the Church Hill Sand, and the Cape Gourdon Formation occur as shoe-string to lensoid bodies where the coast is cut into Mowanjum Sand. They are developed where there is a component of carbonate grains injected into the coastal system, and red sand and white sand are inter-mixed, where aeolian erosion of Mowanjum Sand is direct, and where there is a dominance of alluvial fans shed onto the upper part of the coast, respectively.

The Holocene stratigraphic units occur mainly in eight types of standard sequences:

Type 1 sequence consists of:
1. Shoonta Hill Sand
2. Eighty Mile Beach Coquina, or Cable Beach Sand
3. Port Smith Sand

Type 2 sequence consists of:
1. Horsewater Soak Calcarenite
2. Kennedys Cottage Limestone
3. Willie Creek Calcarenite

Type 3 sequence consists of:
1. Sandfire Calcilutite (as Lagrange Calcilutite Member), with or without the Race Course Plains Coquina
2. Port Smith Sand

Type 4 sequence consists of:
1. Sandfire Calcilutite (as Lagrange Calcilutite Member), with or without the Race Course Plains Coquina
2. Sandfire Calcilutite (as Crab Creek Calcilutite Member)
3. Port Smith Sand

Type 5 sequence consists of:
1. Shoonta Hill Sand
2. Sandfire Calcilutite (with or without the Race Course Plains Coquina)
3. Port Smith Sand

Type 6 sequence consists of:
1. Shoonta Hill Sand
2. Church Hill Sand
3. Mowanjum Sand

Type 7 sequence consists of:
1. Church Hill Sand
2. Barnhill Sand
3. Mowanjum Sand

Type 8 sequence consists of:
4. locally Shoonta Hill Sand
5. Cape Gourdon Formation
6. Cable Beach Sand, Barnhill Formation, or Mowanjum Sand

The environmental setting of each of these sequences are as follows:

Type 1: formed along high energy, open prograding coasts
Type 2: formed along high energy, open prograding coasts, earlier in the Holocene
Type 3: formed along more protected, lower energy coasts
Type 4: formed along more protected, lower energy coasts
Type 5: formed along high-energy retreating coasts, eroding Holocene sediment

Type 6: formed along high-energy coasts eroding earlier Quaternary sediment

Type 7: formed along high-energy coasts eroding earlier Quaternary sediment

Type 8: formed along high-energy coasts eroding earlier Quaternary sediment

These standard sequences provide a useful tool for reconstructing depositional history at a given location, and the position of the stratigraphic interfaces within them relative to present sea level, to be described later, can be used to determine former position of sea level earlier in the Holocene.

Table 7

Summary of radiocarbon ages in yrs BP for the Holocene stratigraphic units

Formation	Range of radiocarbon ages (yrs BP) derived from the various Formations
Shoonta Hill Sand	1190 ± 170, 2440 ± 190
Eighty Mile Beach Coquina	3680 ± 210
Cable Beach Sand	1090 ± 160, 2100 ± 180
Port Smith Sand	3520 ± 200, 3680 ± 210, 4320 ± 220
Race Course Plains	1285 ± 150, 2290 ± 180, 1510 ± 210,
Coquina	2350 ± 225, 3625 ± 260
Sandfire Calcilutite	1390 ± 170, 3170 ± 130, 3415 ± 260, 4070 ± 220, 4470 ± 120, 5070 ± 270, 7450 ± 190
Sandfire Calcilutite (Crab Creek Member Calcilutite)	7280 ± 290
Sandfire Calcilutite (Djugun Member)	3170 ± 180
Barn Hill Formation	900 ± 100, 2740 ± 120
Kennedys Cottage Limestone	5500 ± 160, 5590 ± 240
Willie Creek Calcarenite	3060 ± 600, 6910 ± 180
Christine Point Clay	5310 ± 260

The correlation in terms of sedimentary regimes of the current Holocene lithosome units and the earlier Holocene (mainly calcarenitic) units is shown in Table 8.

Sequences Type 1, Type 2, and Type 3 occur ubiquitously throughout the region, and where they are locally developed, indicate a relatively stabilised system of coastal sediment accumulation. Type 1 sequences occur in prograded open high energy coasts, such as at Cable Beach. The earlier Holocene stratigraphy in embayments and of upwardly shoaled barriers emanating from headlands of embayments is a Type 2 sequence. Type 3 sequence is located under the shoaled tidal flats of protected embayments such as Lagrange Bay, Cowan Creek and Willie Creek, and under Roebuck Plains. For the Roebuck Plains, Type 3 sequence indicates that most of the embayment had remained within the same depositional system throughout the Holocene, with little geomorphic change besides that associated with coastal progradation and intra-embayment shoaling. The more protected parts of Roebuck Bay, to its north, and those parts that are repositories for tidal creek mouth fan sedimentation (ebb-tidal delta) are underlain by Type 4 sequence.

Sequence Type 5 signals that the coast is in retreat. Essentially a Type 3 sequence has been truncated at the coast, and a barrier dune (underlain by the Shoonta Hill Sand) is perched on the cliff cut into the eroded coast.

Sequences Types 6 and 7 signal that aeolian coastal processes have been dominant, and that coastal erosion has been incising pre-Holocene materials, and that such materials have been and are being reworked into and mixed into Holocene sedimentary systems. Sequence Type 8 signals alluvial sedimentation along a retreating coast cut into pre-Holocene materials, and that alluvial fan sediments are interdigitating and interacting with Holocene coastal sediments forming under beaches and dunes.

Table 8

Correlation between stratigraphic units formed under modern lithotopes and their earlier Holocene equivalents

Modern depositional lithosome and its stratigraphic unit	Equivalent earlier Holocene stratigraphic unit
Shoonta Hill Sand = coastal dune sand	Horsewater Soak Calcarenite
Cable Beach Sand = beach sand	Kennedys Cottage Limestone
Cape Boileau Calcarenite Member = beachrock in the Cable Beach Sand	beachrock in the upper Kennedys Cottage Limestone
Lombadina Conglomerate Member = reworked beachrock in the Cable Beach Sand	conglomerate zones in the upper Kennedys Cottage Limestone
Port Smith Sand = low tidal sand and shelly sand	Willie Creek Calcarenite
Sandfire Calcilutite = tidally deposited carbonate mud	locally occurring calcilutite (still referred to the Sandfire Calcilutite)
Race Course Plains Coquina = shell gravel in cheniers	locally occurring coquina (still referred to the Race Course Plains Coquina)
Eighty Mile Beach Coquina = shell gravel concentrate	no equivalent unit earlier in the Holocene
Barn Hill Formation = coastal dunes interacting with red sand dunes	no equivalent unit found earlier in the Holocene
Church Hill Sand = coastal red sand	no equivalent unit found earlier in the Holocene

Recognition of these standard sequences thus provides a powerful tool for reconstructing long-term depositional history and coastal development during the Holocene in the region. For a majority of cases, the standard sequences of Type 1 and Type 3 show that sedimentation style can remain relatively constant for a given area throughout the Holocene.

However, the stratigraphy at some sites illustrates that major changes in geomorphic setting were effected during the Holocene to alter local sedimentation styles from protected, low energy to exposed, high energy, or that low energy coastal progradation has been punctuated by periods of retreat. Sites at Wallal Downs, Mandora, the Cable Beach area, and Camp Inlet exemplify these patterns (Figures 11, 13, 25–27). For those areas that reflect alternating progradation and coastal retreat, the coastal plain is a mud flat with lines of stranded barriers and cheniers, the latter recording the periods of coastal retreat, as marked by shell grit, gravel, and perched dunes on former seacliffs cut into mud (Figure 26).

Today, the coast at Wallal Downs along Eighty Mile Beach is an exposed high energy beach system, with well winnowed shell gravel forming on the beach face. The standard stratigraphic sequence at the shore is Type 1, reflecting the currently active high energy setting. There are no mangroves along the seafront there, but the Sandfire Calcilutite, denoting protected deposition under mangrove cover, is locally exposed along the eroding beach face indicating that the coastal dune barrier is retreating over former mangrove environment deposits. To landward, leeward of the entire coastal dune barrier, there are low coastal flats (Samphire Marsh), up to 10 km wide, underlain by the Sandfire Calcilutite (in a Type 3 sequence). The occurrence of the calcilutite in these settings suggests that, earlier in the Holocene, mangrove depositional environments were more widespread in the area.

The coast at Mandora is another exposed high energy beach system, but here there is a local mangrove-lined tidal creek semi-barred by a dune barrier. The standard stratigraphic sequence along the main coast, again, is Type 1. Local cliffs, however, expose a large lens of Sandfire Calcilutite (Figure 25), indicating that mangrove deposition was greater in extent than today. To landward of this locality, there also are low coastal flats, contiguous with those mentioned above, underlain by the Sandfire Calcilutite. The occurrence of calcilutite in this location also suggests that, earlier in the Holocene, mangrove depositional environments were more widespread. In this location, also, the coast is retrograding, and Shoonta Hill Sand comes to sharply overlie the Sandfire Calcilutite (Type 5 sequence).

The coast at Cable Beach consists of a barrier underlain by Shoonta Hill Sand juxtaposed against, and partly perched on Horsewater Soak Calcarenite, which both act as a barrier to a shore-parallel lowland underlain by Sandfire Calcilutite, illustrating that this area was once a protected embayment partially barred by an aeolian barrier (now indurated to become the Horsewater Soak Calcarenite).

The Camp Inlet area illustrates two variations on the standard stratigraphic patterns. The southern part of the coast is an exposed high energy beach system, but there also is a local exposure of a large lens of Sandfire Calcilutite (Figure 11), indicating mangrove sediment deposition earlier in the Holocene in a former erosional channel whose sedimentary fill (Christine Point Clay overlain by Sandfire Calcilutite) is now being truncated by the coastal retreat. Further to the north, a large coastal erg of white sand (Shoonta Hill Sand) is retreating landwards and burying modern mangrove-vegetated lagoonal deposits – in effect, creating a sequence of Shoonta Hill Sand sharply overlying Sandfire Calcilutite.

Two regional patterns emerge from these stratigraphic data from Wallal Downs, Mandora, Cable Beach, and Camp Inlet areas: that there have been major geomorphic changes centred on the Wallal Downs to Mandora sector (Tract 4 of Figure 4); and that there also have been marked coastal adjustments in local areas of Dampier Peninsula. The coastal stratigraphy in the Wallal Downs to Mandora sector illustrates a change from mud-dominated sedimentation under mangrove cover to high energy beach/dune sedimentation. The belt of mud-dominated sedimentation, which resulted in the accumulation of the Sandfire Calcilutite, is located in two settings, an older and a younger setting.

In the older setting, carbonate mud sedimentation was centred on a relict, buried, funnel-shaped drainage channel inferred to have existed in this region. The data suggest that this relict drainage channel earlier in the Holocene once functioned as a deeply indented mangrove-lined tidal marine funnel-shaped embayment. The occurrence of Holocene carbonate mud deposits within this embayment, however, also would suggest that the Salt Creek drainage line that leads to this embayment was not functioning as a terrigenous sediment source in the Holocene. Evidence of older calcilutites further inland along the embayment suggests that the Salt Creek drainage line was not functioning as a terrigenous sediment source for this embayment for at least the latter part of the Pleistocene.

In the younger setting, carbonate mud sedimentation occurs in the terrain behind shore-parallel ridges, where, by shoaling, it formed the low coastal flats. During this time, it would appear that the main coast prograded by sedimentation in a series of mangrove-vegetated lagoons and embayments sheltered behind and between barrier ridges. The current situation along the Wallal Downs – Mandora coastal tract is one in which high-energy coastal deposits have replaced this younger barrier-and-lagoon configuration.

In the Camp Inlet area, a sheltered embayment (partly barred by aeolian barrier deposits) had been filled with mud, but with erosion of the barriers, remobilisation of sand, and concomitant retreat of the coast, the mud deposits (Sandfire Calcilutite) have been exposed at the seafront of the coast, and Shoonta Hill Sand has retreated over them (Type 5 sequence).

Local areas centred on the Dampier Peninsula also indicate that there have been some major coastal geomorphic readjustments during the Holocene. This is evidenced by the retreat of Holocene sand barriers (Shoonta Hill Sand) over carbonate mud deposits (Sandfire Calcilutite) that had accumulated in protected zones behind a barrier of Horsewater Soak Calcarenite.

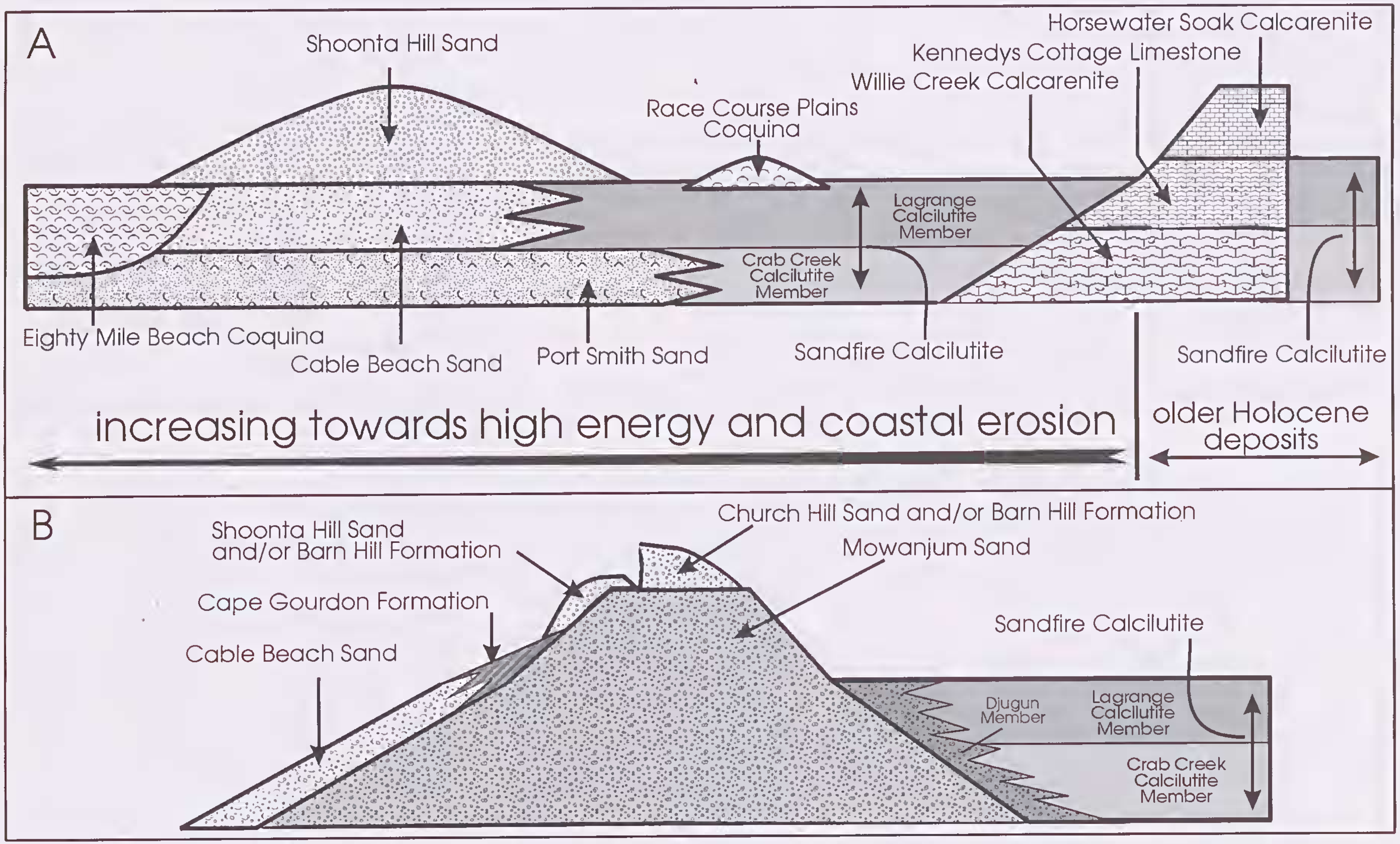


Figure 32. Summary of stratigraphic relationships of Holocene units. A. Marine-derived, and coastal prograding units, arranged to indicate stratigraphic relationships from low energy to high energy and retrograding. B. Array of stratigraphic units and their inter-relationships where the Holocene units interact with the Pleistocene Mowanjum Sand.

The general erosional nature of the coast in the Dampier Peninsula region, where many Holocene sand barriers are in general retreat, would suggest that there has been erosion, breaching and collapse of weakly cemented earlier Holocene limestone barriers and of strongly cemented Pleistocene limestone barriers in some localities in offshore/nearshore situations, or alongshore anchor situations, fundamentally changing the hydrodynamics of the coastal zone, and exposing the coast to sustained wave attack. These changes in limestone barrier and sand barrier dynamics, however, are not widespread in the region. For instance, the limestone barriers at Willie Creek and Cape Boileau (a Holocene limestone barrier and a Pleistocene limestone barrier, respectively) still protect their leeward embayments.

The detailed study of Cable Beach by Wright *et al.* (1982) proved useful to explaining the distribution of facies in high energy coastal environments. Wright *et al.* (1982) described Cable Beach as having an overall concave upward profile with low gradient and dissipative subtidal and low-tidal zones, and steeper more reflective mid-tidal and high-tidal zones. With time-averaged predictive estimates of wave work over the lunar half cycle for different points on the intertidal beach profile, Wright *et al.* (1982) suggested a relatively uniform distribution of wave work over most of the profile but with maxima in the middle of the low-tidal zone and over the lower part of the high-tidal zone. Most of the work over the low-tidal and mid-tidal zones was performed by unbroken shoaling waves rather than by surf zone processes, with surf zone processes dominating over the high-tidal zone. The nature of the surf zone processes varied across the profile as local gradient and degree of reflectivity changed with changing tide level. Translated to facies variations within high energy sandy coasts of this study, these results confirm the transition of wave-generated, and wave-dominated sedimentary structures in the beach swash zone equivalent to the Cable Beach Sand, and a relatively lower energy environment equivalent to the Port Smith Sand.

Sea-level indicators in the stratigraphic units and sea-level history of the Canning Coast

If correctly and accurately identified, tidal level markers and mean sea level markers provide a powerful tool to interpreting sea-level history in a given region. From the plethora of lithologically distinct modern stratigraphic units along the Canning Coast, a number of tide markers have emerged. Within a given region, tidal level markers can be used to point to the position of MSL. Thus, for example, if the tidal ranges are known, a tidal level marker situated at HAT, or EHWS, can be used to interpolate the position of local MSL. However, a major assumption in transferring modern tidal level markers, as they relate to modern MSL, to interpret older sequences is that tidal regimes 7000–2000 yrs BP, for a given tract of coast, were similar to those of today. With Earth-axis precession, there may have been a shift in tidal amplitude, but the discussion below is provided in the context that Earth-axis precession has not altered the amplitude of the tidal range in the region significantly enough to render comparison of earlier Holocene tidal markers and modern tidal markets invalid. In the discussion that follows, the tidal level markers are used to infer the former relative position of MSL for a given locality, *i.e.*, the interpretations are focused locally, and not regionally applied.

Some stratigraphic interfaces and sedimentary markers in determining tidal levels along the Canning Coast, and an assessment of their reliability, are presented in Table 9.

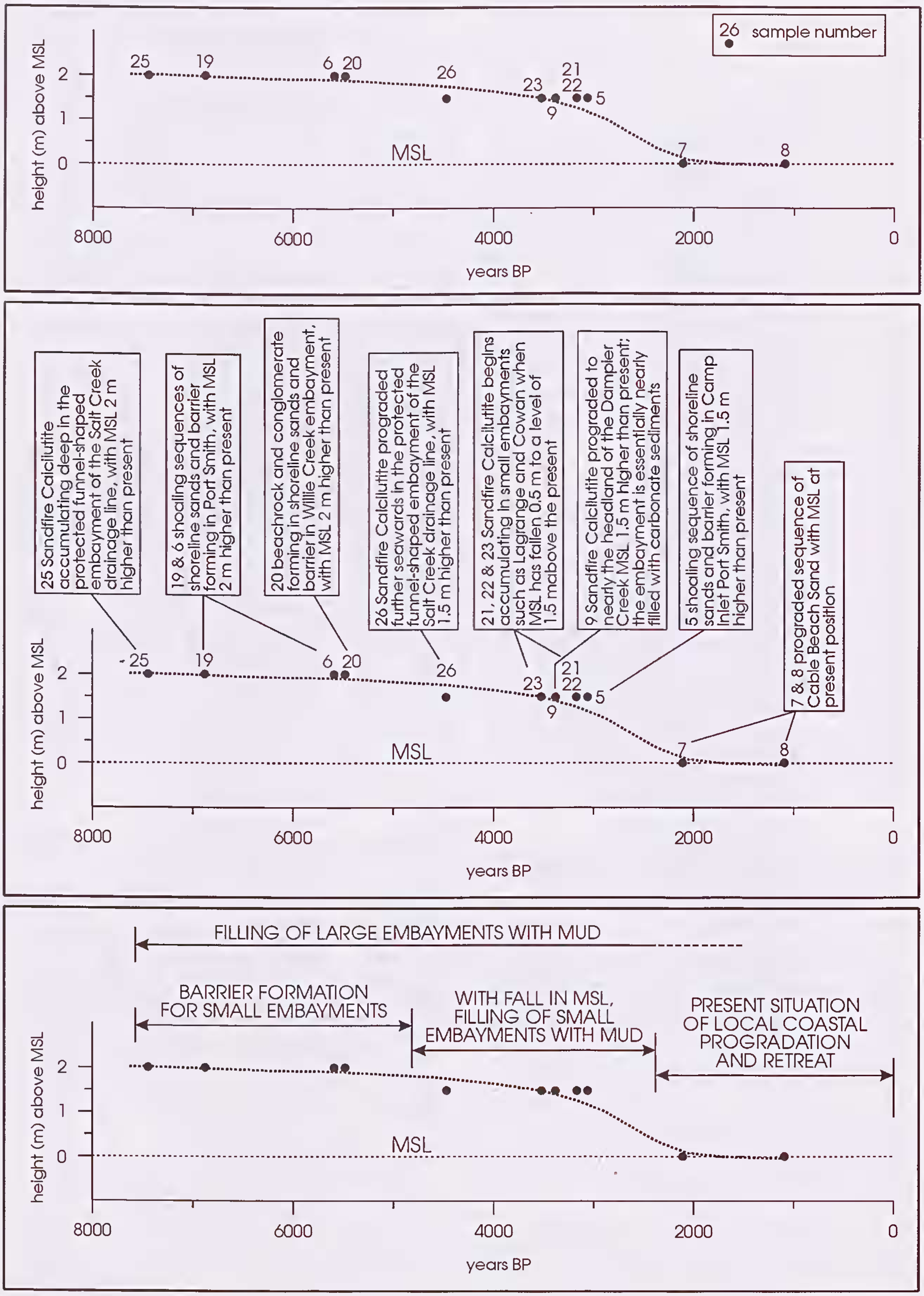
Radiocarbon dating of some of these interfaces and sedimentary markers shows that MSL was higher earlier in the Holocene. Using 11 sites, critical markers and stratigraphic interfaces that have been dated, and data on the level that these markers and interfaces occur in relation to present MSL or other tidal levels are presented in Table 10.

From Table 10, samples 6, 19, 20, 23 and 25 show MSL was 2 m above present in the period 7500 yrs BP to 4500 yrs BP. Samples 5, 21, 22, 23 and 26 show that MSL was about 1.5 m above present level between 4500 and 2100 yrs BP, and sample 7 shows that MSL was at about its present position by 2100 yrs BP. While MSL remained at a position of + 2 m for the period 7500 yrs BP to 4500 yrs BP, there appears to have been a progressive fall in relative MSL between 4500 yrs BP and 2100 yrs BP. The radiocarbon ages of the samples and their indication of relative MSL are shown in Figure 33. This reconstruction of relative MSL history is preliminary as there are not enough samples to accurately plot the history in a robust manner. It does however provide an indication of the behaviour of MSL over the past 7500 years. Also, it should be borne in mind that this reconstruction crosses a wide geographic latitude wherein the tidal range difference (from Cape Keraudren to Broome) is *circa* 2 m, and that each data point on the graph of Figure 33 therefore represents the *local* former MSL position. Information on other samples that have been radiometrically dated, where relevant, are annotated on Figure 33 to provide a comparative and contextual MSL history.

Fossil and subfossil assemblages of molluscs and mangroves

As noted in the section on Terms and Definitions, mollusc shells and mangrove vegetation as fossils and subfossils were used in this study: (1) to characterise some of the Holocene Formations; (2) to determine the environment of deposition of some of the older Formations and; (3) to assess the extent of reworking and mixing that has taken place along the coast. Of the range of assemblage types (*in situ* biocoenosis, autochthonous biocoenosis, allochthonous biocoenosis, allochthonous partial biocoenosis, mixed biocoenosis/thanatocoenosis, and allochthonous thanatocoenoses), the types that are present along the Canning Coast, with examples, are listed in Table 11.

Identifying autochthonous biocoenoses is particularly important in the muddy tidal flat Formations because, as noted above, by their nature of fine-grained particle sizes, such Formations signal relatively little transport of shell into and out of the lithotope, and further, if accumulated under mangrove cover, shell content in the underlying mud may directly reflect the composition of molluscs in


26 sample number
height (m) above MSL
MSL
years BP
25 Sandfire Calcilutite accumulating deep in the protected funnel-shaped embayment of the Salt Creek drainage line, with MSL 2 m higher than present
19 & 6 shoaling sequences of shoreline sands and barrier forming in Port Smith, with MSL 2 m higher than present
20 beachrock and conglomerate forming in shoreline sands and barrier in Willie Creek embayment, with MSL 2 m higher than present
26 Sandfire Calcilutite prograded further seawards in the protected funnel-shaped embayment of the Salt Creek drainage line, with MSL 1.5 m higher than present
21, 22 & 23 Sandfire Calcilutite begins accumulating in small embayments such as Lagrange and Cowan when MSL has fallen 0.5 m to a level of 1.5 mabove the present
9 Sandfire Calcilutite prograded to nearly the headland of the Dampier Creek MSL 1.5 m higher than present; the embayment is essentially nearly filled with carbonate sediments
5 shoaling sequence of shoreline sands and barrier forming in Camp Inlet Port Smith, with MSL 1.5 m higher than present
7 & 8 prograded sequence of Cable Beach Sand with MSL at present position
FILLING OF LARGE EMBAYMENTS WITH MUD
BARRIER FORMATION FOR SMALL EMBAYMENTS
WITH FALL IN MSL, FILLING OF SMALL EMBAYMENTS WITH MUD
PRESENT SITUATION OF LOCAL COASTAL PROGRADATION AND RETREAT

this biotope (as vagile, or in-faunal, or encrusting forms). Mid- to high-tide mollusc assemblages inhabiting muddy substrates are markedly different to mid- to low-tidal mollusc assemblages that inhabit muddy substrates. As such, this difference, if the molluscs are preserved, allows for recognition of two environmentally distinct mud-based biotopes that are preserved as two distinct lithosomes. Hence, two distinct biostratigraphic units can be recognised in the mud lithosome that can also be related to MSL. This distinction is also particularly useful when there is a need to interpret Pleistocene shelly calcilutites in this region.

Along the Canning Coast, while some assemblages are close to being autochthonous biocoenoses, there are patterns of coastal erosion and reworking that have resulted in a multitude of assemblages of mixed shells signalling derivation from various environments, multiple phases of mixing, and changes in coastal environment in terms of substrates and wave exposure. Thus, while molluscan shell assemblages can play a useful role in palaeo-environmental reconstructions, there is the real and complicating factor that must be borne in mind that shells in the various Holocene Formations have undergone (prevailing) wave reworking, transport, (periodic) storm reworking and concentrating, and cyclone-induced reworking, concentrating, transport and mixing, and their provenance may be difficult to determine.

Notwithstanding the effects of reworking, transport, and mixing, there also are difficulties in interpreting biocoenotic setting and formative environments of enclosing sediments because of the potential effects of Holocene regional climate changes driven, for example, by Earth-axis precession (Semeniuk 1995b; Semeniuk & Semeniuk 2005). In this context, a tidal flat today may be inhabited by a faunal assemblage subtly compositionally different to that inhabiting the same type of tidal flat, say, 2000 years ago. The shell accumulations are both autochthonous biocoenoses, but one is 2000 years old, and the other is extant. Bioturbation, tidal reworking or wave reworking (*within*) the lithotope can mix the two assemblages.

In this study, there was a focus on two types of fossils and subfossils: (1) mollusc-dominated fauna, and (2) mangrove (vegetation) assemblages and their accompanying molluscs.

Fossil and subfossil assemblages of molluscs

Molluscan shells can be a powerful tool in defining stratigraphic units and in reconstructing palaeoecology. Where shells are environment-specific and have accumulated *in situ* or autochthonously (thus representing life assemblages or biocoenoses), they can provide information on environment of deposition, and position of the enclosing sediment relative to MSL. Biocoenoses accumulating under seagrass cover (*e.g.*, Shark Bay and Rockingham; Logan *et al.* 1970; Searle *et al.* 1988) provide examples of such deposits, and have been used to reconstruct Pleistocene palaeo-environments (Semeniuk 1997).

Even if reworked (and representing thanatocoenoses), shells can provide information on the environment of the original biocoenosis, and/or the extent that shells have been transported, concentrated, or mixed. Where shells are environment-specific but have later mixed as thanatocoenoses, they provide valuable information on the extent that transport and mixing have taken place.

In the first instance, the various species of fossil and sub-fossil molluscs are useful in this study of the Canning Coast to characterise Formations and members. However, in a broad biostratigraphic and palaeo-environmental context, a critical factor in determining whether shells are preserved within their lithosome, and thus determining various types of biocoenoses and thanatocoenoses, is information on habitat of species in this region. In this study, many molluscs are observed and collected from the following habitats: mangrove-vegetated mid- to high tidal mud flats, low to mid- tidal mud flats, low tidal sand flats, inter-tidal rocky shores, and beaches, and hence could be directly used for determining habitat-specificity. In addition, for a number of the fossil and subfossil species, information on habitat was obtained from texts and Western Australian Museum records. However, overall, there was not enough information in the literature to characterise the habitat of many of these species to be environmentally specific enough to be useful in reconstructing former biotopes. Many of the texts on shell identifications, while useful in identifying species, provide vague descriptions of habitat, or too imprecise description of habitat (what is required is substrate type, or the variety of substrate types an organism may inhabit, and its tidal level as to whether it is low, mid-tidal or high-tidal).

Another complication in palaeo-environmental reconstructions and determining various types of biocoenoses and thanatocoenoses is that many species cross habitat boundaries. For instance, *Antigona chemnitzii*, *Arca avellana* and *Venus lamellaris* are not substrate-specific and can inhabit sand, muddy sand, mud, and for *Venus lamellaris* even rocks, and hence they are not habitat-specific. Some species are not depth-specific and hence do not even signal intertidal conditions (*e.g.*, *Arca avellana*). Their usefulness as palaeo-environmental indicators thus is diminished. Essentially, not enough autoecological information is available in the literature on most of the mollusc species encountered in this study, and not enough detailed habitat notes are provided in identification text books for use in defining species-and-habitat relationships. There are exceptions: mangrove-associated molluscs are good examples of environment-diagnostic shell assemblages, and if found outside of their lithotope are reliable indicators of transport. Similarly, many of the shells that inhabit sandy substrates also are environmentally diagnostic.

Saccostrea cucullata and *Nassarius dorsatus* occur in a number of habitats, nevertheless they are used in this study as a measure of environmental provenance. For instance, while *Saccostrea cucullata* can occur in two habitats (*viz.*, rocky shores and on mangrove trunks), it has been used as environmentally indicative. If it inhabits

◀ Figure 33. A. Reconstructed sea level history for the Canning Coast 7500 yrs BP to the present. B. The local sedimentary and/or geomorphic events specific the radiocarbon dates as they relate to the sea level history. C. The major sedimentary events and geomorphic events related to the sea level history.

Table 9

Key stratigraphic interfaces and sedimentary markers for determining tidal level

Stratigraphic interface or sedimentary marker	Tidal level	Comments on estimated reliability	Where used in this study in conjunction with radiocarbon dates
Shoonta Hill Sand on Cable Beach Sand	HAT	indicator of HAT to within 0.5 m	within the stratigraphic sequences at Cable Beach (Figure 13), and within the stratigraphic sequences for the earlier Holocene equivalents of Horsewater Soak Calcarenite overlying Kennedys Cottage Limestone at Camp Inlet (Figure 11), Willie Creek (Figure 12), and Port Smith (Figure 22)
Shoonta Hill Sand on Sandfire Calcilutite	HAT	indicator of HAT to within 0.25 m	within the stratigraphic sequences at Mandora (Figure 25), and landward of the barrier in Figure 27
Upper surface of beachrock pavement	EHWS	indicator of EHWS to within 0.5 m	within the stratigraphic sequences for the earlier Holocene equivalent Kennedys Cottage Limestone at Port Smith (Figure 22B)
Storm boulder deposit	EHWS, HAT and 1 m above HAT	indicator of HAT to within 1 m	within the stratigraphic sequence for the earlier Holocene equivalent of Kennedys Cottage Limestone at Willie Creek (Figure 12) and Port Smith (Figures 21 and. 22)
Upper surface of Lagrange Calcilutite Member, or Sandfire Calcilutite	~ HAT	indicator of HAT to within 0.5 m, with the complication that the former (earlier Holocene) surfaces may have been geomorphically lowered by wind erosion or tidal sheet erosion	Lagrange Bay (Figure 23), Cowan Creek (Figure 24), Samphire Marsh at Sandfire (Figure 30A) and east Mandora Marsh (Figure 30B)
Contact of agrange Calcilutite Member with Crab Creek Calcilutite Member	~ MSL	indicator of MSL to within 0.5 m with the complication that on a prograded muddy coast mangrove root-structuring may extend 0.5 m into the underlying Crab Creek Calcilutite Member and blur the contact	at Central Eighty Mile Beach (Figure 26)
Lagrange Calcilutite Member on Port Smith Sand	~ MSL	depending on local setting, indicator of MSL to within ± 1.0 m, but accurate enough for precise determination of former MSL	noted to occur, but not specifically used in this study
Bubble-sand structures	MSL-EHWS	indicator of tidal levels above ~ MSL	within the stratigraphic sequence for the earlier Holocene equivalent of Kennedys Cottage Limestone at Willie Creek (Figure 12) and Port Smith (Figures 21 and. 22)
zone of accumulation on the upper beach slope of *Sepia* spp and *Spirula spirula*	~ EHWS - HAT	indicator of tidal levels between EHWS and HAT, but more reliable as an indicator for accumulation at HAT, though storm surges can place these shells above HAT (enclosing sediments need to be assessed as to whether the enclosing sediments are high-tidal or aeolian)	within the stratigraphic sequence for the upper Cable Beach Sand at Cable Beach (Figure 13)
in situ Ceriops trunks in Lagrange Calcilutite Member, or in the Christine Point Clay	~ MHWS	indicator of MHWS tidal level	noted to occur (Figures 10 and 11) but not specifically radiometrically dated in this study
in situ Rhizophora roots in Lagrange Calcilutite Member, or in the Christine Point Clay	~ MSL-MHWN	indicator of MSL-MHWN tidal level	noted to occur (Figure 11) but not specifically radiometrically dated in this study
Pitar shells in Lagrange Calcilutite Member	~ MSL-MHWN	indicator of MSL-MHWN tidal level, *i.e.*, an indicator of MSL to 0.9 m above MSL	within the stratigraphic sequence for the upper Lagrange Calcilutite Member at Dampier Creek (Figure 14)
Saccostrea cucullata shells in Lagrange Calcilutite Member	~ MSL	indicator of MSL tidal level	noted to occur, but not specifically radiometrically dated in this study

Table 10

Radiocarbon ages of key stratigraphic interfaces and sedimentary markers in the Holocene sequences ordered from youngest to oldest

Stratigraphic interface or sedimentary marker	Tidal level of sample	^{14}C age in yrs BP	Interpretation of position of former MSL (ages are rounded off)
Sample 8: shells in Cable Beach Sand (Figure 13)	HAT	1090 ± 160	MSL was at present level at *circa* 1000 yrs BP
Samples 7: shells in Cable Beach Sand (Figure 13)	HAT	2100 ± 180	MSL was at present level by *circa* 2100 yrs BP
Sample 5: shell in the upper Willie Creek Calcarenite as part of shoaled stratigraphic package, with former HAT (contact with aeolian sediments) at *circa* 1.5 m above modern HAT (Figure 11)	*circa* 1 m below modern HAT	3060 ± 600	former MSL was ~ 1.5 m above present MSL *circa* 3000 yrs BP
Sample 21: upper depositional limit of carbonate mud under red sand lens at shore of Cowan Creek; mud is 1.5 m above HAT (Figure 24)	1.5 m above HAT	3170 ± 180	the mud, indicative of the highest level that carbonate mud onlapped the red sand terrain, is located 1.5 m above modern HAT; it indicates MSL was 1.5 m above present *circa* 3200 yrs BP
Sample 22: carbonate mud located 1.5 m above HAT (Figure 23)	1.5 m above HAT	3170 ± 130	the mud, located 1.5 m above HAT, indicates MSL was 1.5 m above present *circa* 3200 yrs BP
Sample 9: *Pitar* shells in upper Lagrange Calcilutite Member located now at HAT (Figure 14)	HAT	3415 ± 260	*Pitar* is a mollusc that inhabits mid- to seaward parts of mangrove environments; now located at HAT, it indicates MSL was *circa* 1.5 m above present *circa* 3400 yrs BP
Sample 23: interface between Lagrange Calcilutite Member and Crab Creek Calcilutite Member located 1.5 m above MSL (Figure 26)	1.5 m above MSL	3520 ± 200	the stratigraphic interface, indicative of the contact between mangrove-influenced sedimentation, and mid- tidal mud accumulation is located 1.5 m above MSL, indicates former MSL was 1.5 m above present *circa* 3500 yrs BP
Sample 26: carbonate mud at 1 m depth; upper surface of section is 1.5 m above HAT (Figure 30)	at HAT	4470 ± 120	the surface of the mud at this location, situated 1.5 m above HAT, indicates MSL was 1.5 m above present *circa* 4500 yrs BP
Sample 20: shell within the conglomerate zone of the upper Kennedys Cottage Limestone (Figure 22)	2 m above HAT	5500 ± 160	the conglomerate, indicative of HAT levels in modern environments, is located 2 m above its modern equivalents; it indicates MSL was 2 m above present *circa* 5500 yrs BP
Sample 6: shell in Kennedys Cottage Limestone, 2 m above present analogue lithotope (Figure 12)	HAT	5590 ± 240	former MSL was 2 m above present MSL *circa* 5600 yrs BP
Sample 19: shell in the upper Willie Creek Calcarenite as part of shoaled stratigraphic package, with former HAT (contact with aeolian sediments) at *circa* 2 m above modern HAT (Figure 22)	HAT	6910 ± 180	former MSL was 2 m above present MSL *circa* 7000 yrs BP
Sample 25: carbonate mud at 2 m depth; upper surface of section is 2 m above HAT (Figure 30)	at HAT	7450 ± 190	the surface of the mud at this location, situated 2 m above HAT, indicates MSL was 2 m above present *circa* 7500 yrs BP

intertidal rocky shores where erosion and shell export are prevalent, and it occurs in nearby sandy beaches or low tidal flat sands, it provides an indication of the occurrence of nearby rocky shores, and that transport from that habitat has occurred. Thus, its occurrence in sediments outside of the mangrove environment signals possible transport from rocky shores. On the other hand, while *Nassarius dorsatus* inhabits a number of intertidal substrates (sand, muddy sand, and mud), it is more common on sand and muddy sand, and so also is environmentally indicative.

A summary listing of species with respect to habitats, synthesised from all sources, is provided in Table 12.

Modern and sub-recent environments where mollusc shells accumulate are as follows:

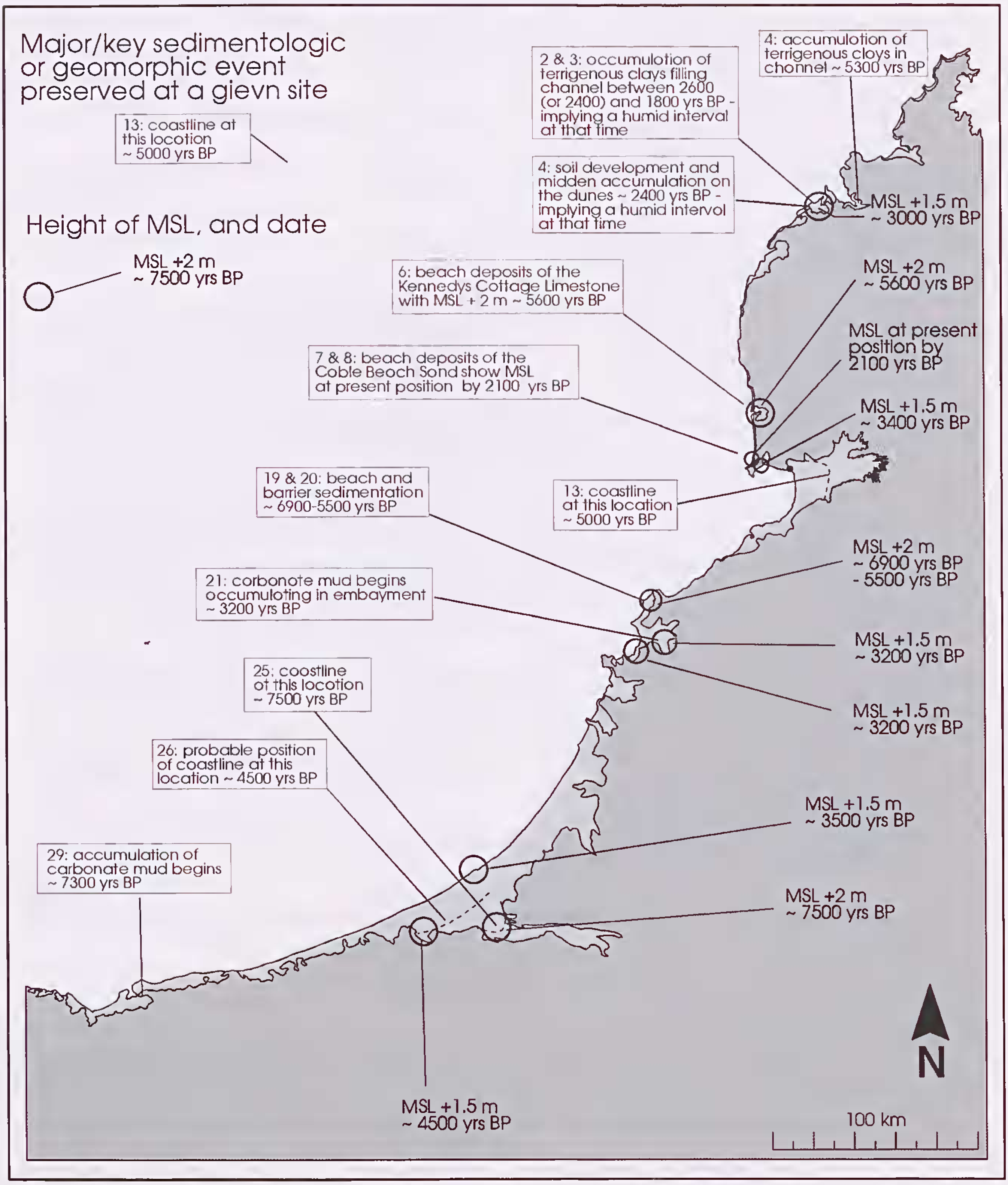


Figure 34. Summary of radiocarbon ages from the various formations. This illustration show the major sedimentoloigic and geomorphic events that have occurred along the Canning Coast, and the position MSL at various (radiocarbon) times.

Table 11

Composition of mollusc assemblage types

Assemblage type	Definition and examples from the Canning Coast
in situ biocoenosis	there are no mollusc shell examples in the Canning Coast region, but some ichno-assemblages may be considered to be *in situ* biocoenoses
autochthonous biocoenosis	shells accumulated under mangrove cover where there is accumulation of the local shells, accumulation of tree trunks, and some *in situ* trees, also are examples of autochthonous biocoenoses along the Canning Coast
allochthonous biocoenosis	oligomictic accumulations of *Donax faba* and its associated molluscs formed within the beach environment and transported to an adjoining environment are examples along the Canning Coast; the shells represent the living mollusc assemblage, but do not occur in their lithotope
allochthonous partial biocoenosis	oligomictic accumulations of cuttlefish (*Sepia* spp) and the rams horn shell (*Spirula spirula*) derived from oceanic habitats and accumulating on the high tidal beach zone is an example of such assemblages along the Canning Coast
mixed biocoenosis/ thanatocoenosis	oligomictic shell accumulation on a beach, with *Donax faba* which inhabits the beach, mixed minimally with other molluscs that have been transported from a variety of low-tidal zones, are examples of mixed biocoenosis/ thanatocoenosis along the Canning Coast; mangrove environments can provide another example in that mangrove-associated molluscs are distinctive, and if accumulated within the mangrove environment, indicate an autochthonous biocoenosis, but if tellinids are transported by storms from mid- tidal mud flats into this environment, the resulting shell assemblage is a mixed biocoenosis/thanatocoenosis
allochthonous thanatocoenosis	these types of shell accumulations are common along the Canning Coast. The descriptor "allochthonous" is somewhat redundant, but is added to be consistent with the other terms, and to emphasise that the assemblage is outside of its biotope, for example, beach sand with *Donax faba* which inhabits the beach, mixed with abundant other molluscs that have been transported from a variety of low tidal zones

1. mud under mangrove cover, with low opportunity for reworking
2. mud in mid-low tidal environments, with higher chance of winnowed shell lag development and reworking through waves and storms
3. low tidal sandy flats, and muddy sand flats, with variable opportunity for reworking, especially after storms and cyclones
4. mid- to low-tidal sandy beaches with high opportunity for reworking and high opportunity for storm concentration, with or without exogenic contribution from adjoining environments
5. rocky shores (either Mesozoic bedrock, Tertiary age ironstone, Pleistocene limestones, or Holocene limestones)
6. zone of flotsam and jetsam at the high tide mark, where there is an accumulation of floaters *i.e.*, *Spirula spirula*, and various species of *Sepia*, deriving from offshore oceanic environments, that float on the high water and are deposited at the high water mark (EHWS and HAT)
7. spits and cheniers where there is concentration of shells during storms,
8. spits and cheniers with a veneer of middens, where Indigenous people have concentrated particular mollusc species
9. deflation hollows of coastal dunes, with middens, where Indigenous people have concentrated particular mollusc species

The main diagnostic or conspicuous molluscs in these environments, with comments on the significance of their occurrence, are presented in Table 13. A selection of the five to ten most abundant species from the list of molluscs that were counted in this study is shown for the main Formations in Figures 35–37.

Accumulations of *Sepia* spp and *Spirula spirula* are derived from the pelagic zone offshore, which in this paper is treated as a single habitat type.

In terms of Formational biostratigraphy, Table 14 presents a summary of the molluscan fauna in the various Formations and members, and their classification in terms of autochthony/allochthony, and biocoenosis/ thanatocoenosis. Comparative information in Tables 12 and 13 on mollusc habitat specificity is used for the interpretations presented in Table 14. In Table 14, note that some mollusc assemblages are separated within a Formation into more refined assemblage types, as based on their oligomictic or polymictic character, and their occurrence in lower, middle or upper parts of a given Formation.

To interpret the provenance and extent of autochthony or allochthony of assemblages, given that some species cross habitat boundaries, there was a focus on habitat-specific shells. The oyster *Saccostrea cucullata* was the exception. As noted earlier, it occurs on rocky substrates (such as Mesozoic rock, Pleistocene limestone, and earlier Holocene limestone) and on mangrove trunks and aerial roots (and so indicating mangrove environments). In this case, the setting of the sediment wherein the oyster is found can provide an indication of where the oyster was derived (*e.g.*, sand-dominated sediment sinks that have nearby rocky shores would suggest a provenance of rocky shores).

However, there are limitations to this comparative palaeoecological aspect of the study, in that shells collected from modern environments were more numerous and hence showed greater diversity than those collected from limestone cliffs that expose earlier Holocene calcarenites. Hence there are difficulties with directly comparing modern subfossil and fossil assemblages with earlier Holocene assemblages. Nonetheless, the comparisons and discussions that follow rest on the fact that the earlier Holocene calcarenites, in fact, are not as fossiliferous as the modern sediments, and that the comparative collections obtained from the modern and the lithified Holocene Formations, relatively, are indicative of abundance and of diversity. The results, however, should be viewed as preliminary for the comparisons between Cable Beach Sand and Kennedys Cottage Limestone, and between Port Smith Sand and Willie Creek Calcarenite.

Table 12

Habitat specific molluscs

Habitat	Species
Mangrove environments	*Cerithidea anticipata, Cerithidea cingulata, Cerithidea reidi, Chicoreus cornucervi, Littoraria* cf. *cingulata, Nerita squamulata, Nerita undata, Pitar* sp., *Telescopium telescopium, Terebralia palustris, Terebralia sulcata, Saccostrea cucullata,* species of Teredinidae
Mud and muddy sand	*Anadara granosa, Trisidos tortuosa, Paphies striata, Placuna placenta, Tellina capsoides, Anadara granosa*
Sand and muddy sand	*Anadara crebricostata, Nassarius dorsatus, Strombus campbelli*
Sand	*Asaphis violascens, Austriella sordida, Bulla ampulla, Bulla guoyii, Callista impar, Donax faba, Dosinia deshayesii, Dosinia incisa, Duplicaria duplicata, Ficus eospila, Fragum hemicardium, Mactra abbreviata* cf. *meretriciformis, Mactra incarnatae, Mactra westralis, Melo amphora, Murex* cf. *acanthostephes, Naticarius alapapiliones, Oliva lignaria, Paphia crassisula, Paphies heterodon, Pinna bicolor, Placamen gravescens, Polinices conicus, Solen kajiyamai*
Coarse sand and rubble	*Exotica assimilis*
Rock pavement (including beachrock pavement)	*Conus textile, Conus victoriae, Cronia aurantia, Cypraea gracilis, Cypraea pyriformis, Saccostrea cucullata, Turbo bruneus*
Rocky shore	*Arca ventricosa, Barbatia foliata, Chama reflexa, Herpetopoma atrata, Nerita undata, Planaxis sulcatus, Saccostrea cucullata, Spondylus wrightianus, Trochus maculatus*

On a final note, palaeoecological studies and the assessment and classification of fossil assemblages as to their autochthony or allochthony should/could be undertaken at the bed level, and sometimes at the lamination level, as often the variation of preservation type is expressed at this scale. However, since the Canning Coast is quite dynamic, variation of preservation type would more likely be expressed at the metre-scale to decimetre-scale. With local progradation and rapid burial and stranding of sediments and associated fauna, there may be preservation of types, measured on the decimetre scale. Then with local retreat and reworking of the same sediments, there can be alternating beds of fossils and subfossils of various preservation types, measured on the metre scale. As such, fossil and subfossil assemblages can be alternating autochthonous and allochthonous biocoenoses; some are interlayered autochthonous and allochthonous biocoenoses, and mixed allochthonous biocoenoses/ thanatocoenoses; some layers can be fully allochthonous thanatocoenoses.

Fossil and subfossil assemblages of mangroves

Mangrove vegetation, if preserved, also can be a powerful tool in defining stratigraphic units and in reconstructing palaeoecology. Often, mangroves have been preserved as *in situ* trunks, and in this context they provide information about tidal levels of the deposits in which they are embedded (Semeniuk 1983). *Avicennia marina, Rhizophora stylosa* and *Ceriops tagal* are three mangroves that have been observed *in situ* in mud Formations. All three species have distinctive root structures (Semeniuk *et al.* 1978), and wood anatomy, to permit ready identification. *Avicennia marina* more commonly is found as fallen trunks, branches, and wood fragments within a mud Formation. Linked with the deposits that contain the fossil mangrove trees, of course, are mangrove-associated molluscs, as described above *viz., Cassidula angulifera, Cerithidea cingulata, Certhidea obtusa, Ellobium aurisjudae, Pitar* sp., *Terebralia palustris, Terebralia sulcata, Telescopium telescopium* and *Saccostrea cucullata*. The total aggregations of fossil trees and shells are autochthonous biocoenoses.

Middens

Indigenous people in the region over the past several thousands of years have contributed to the formation of specific types of thanatocoenoses. In the various sub-regions of the Canning Coast, and at different times of the middle to late Holocene, they have brought particular species of molluscs to coastal dune and chenier lithotopes. These resulting various (midden) thanatocoenoses have been described in Table 13.

Separating middens form natural sedimentary accumulations is discussed further here. There is little problem in recognising middens where they are located outside the realm of natural sedimentary processes (*e.g.*, shells of *Anadara granosa* accumulating in the Crab Creek Calcilutite Member would be a sedimentary deposit, while shells of *Anadara granosa* in the Barn Hill

Figure 35. Shell assemblages of the Lagrange Calcilutite Member, Crab Creek Calcilutite Member, Cable Beach Sand, chenier in the Race Course Plains Coquina, Kennedy Cottage Limestone, and Willie Creek Calcarenite. Bar scale is 1 cm. ▶

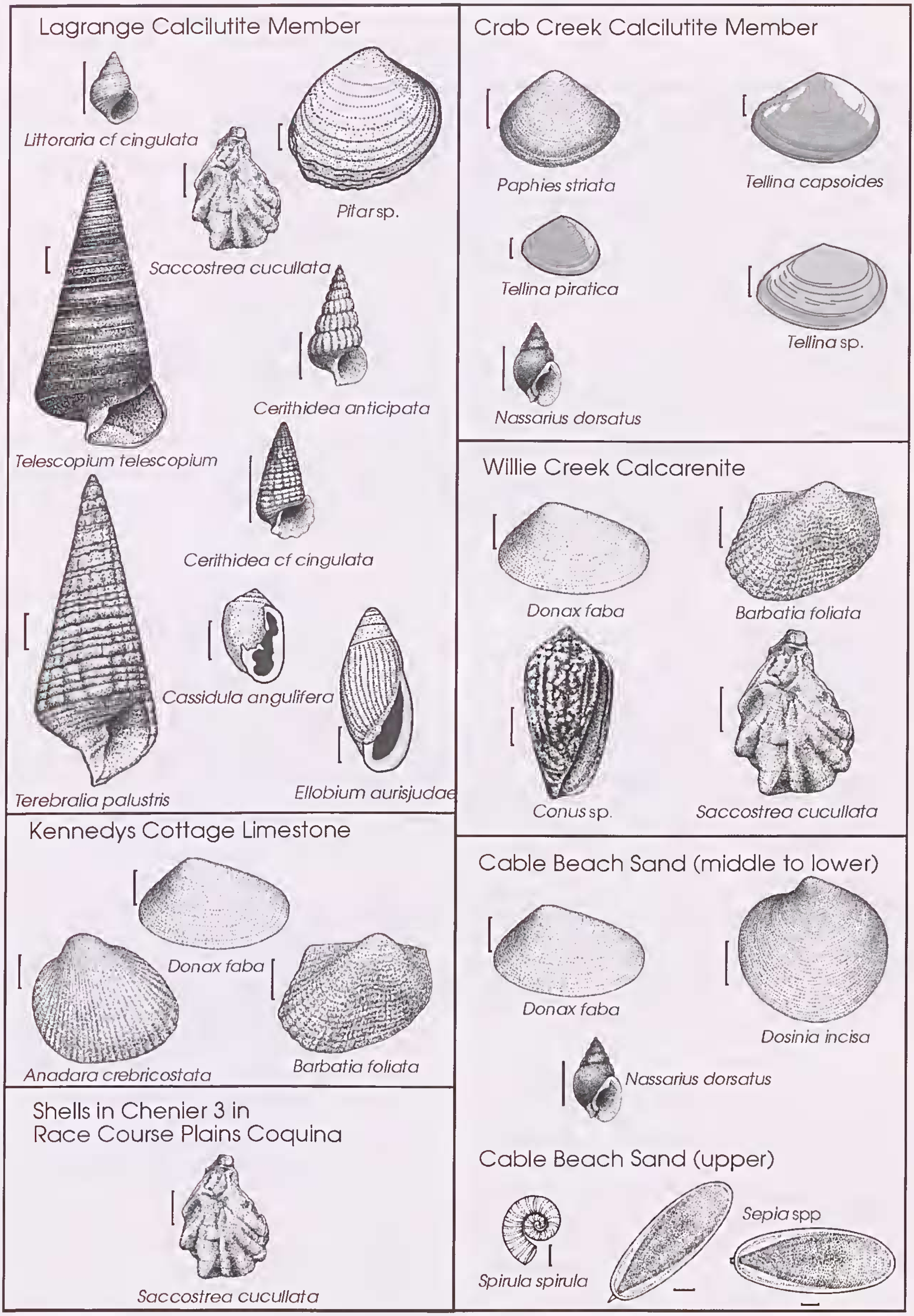

Lagrange Calcilutite Member
Littoraria cf cingulata
Pitar sp.
Saccostrea cucullata
Cerithidea anticipata
Telescopium telescopium
Cerithidea cf cingulata
Cassidula angulifera
Terebralia palustris
Ellobium aurisjudae
Crab Creek Calcilutite Member
Paphies striata
Tellina capsoides
Tellina piratica
Tellina sp.
Nassarius dorsatus
Willie Creek Calcarenite
Donax faba
Barbatia foliata
Conus sp.
Saccostrea cucullata
Kennedys Cottage Limestone
Donax faba
Anadara crebricostata
Barbatia foliata
Shells in Chenier 3 in
Race Course Plains Coquina
Saccostrea cucullata
Cable Beach Sand (middle to lower)
Donax faba
Dosinia incisa
Nassarius dorsatus
Cable Beach Sand (upper)
Spirula spirula
Sepia spp

Table 13

Summary of main environments and their mollusc assemblages along the Canning Coast

Environment (habitat)	Main, diagnostic, or conspicuous molluscs	Comments
mud under mangrove cover with low opportunity for reworking	*Cassidula angulifera, Cerithidea cingulata, Certhidea obtusa, Ellobium aurisjudae, Nerita undata, Pitar sp., Terebralia palustris, Terebralia sulcata, Telescopium telescopium* and *Saccostrea cucullata*	these shells represent mainly an autochthonous accumulation
mud in mid-low tidal environments, with higher chance of winnowed shell lag development and reworking through storms	*Anadara granosa, Anomalocardia squamosa, Paphies striata, Tellina capsoides, Tellina piratica* and *Nassarius dorsatus*	these shells represent mainly an autochthonous accumulation
low tidal sandy flats, and muddy sand flats with variable opportunity for reworking, especially during storms and cyclones	*Anadara crebricostata, Anomalocardia squamosa, Asaphis violascens, Austriella sordida, Bulla ampulla, Bulla guoyii, Callista impar, Donax faba, Dosinia deshayesii, Dosinia incisa, Duplicaria duplicata, Ficus eospila, Fragum hemicardium, Mactra abbreviata* cf. *meretriciformis, Mactra incarnatae, Mactra westralis, Melo amphora, Murex* cf. *acanthostephes, Nassarius dorsatus, Naticarius alapapiliones, Oliva lignaria, Paphia crassisula, Paphies heterodon, Pinna bicolor, Placamen gravescens, Polinices conicus, Solen kajiyama* and *Strombus campbelli*	this assemblage of shells represents mainly an autochthonous accumulation
mid- to low-tidal sandy beaches with high opportunity for reworking, and high opportunity for storm concentration, without exogenic contribution from adjoining environments	*Donax faba, Dosinia incisa, Paphies* sp. and *Nassarius dorsatus*	these shells represent mainly an autochthonous accumulation, though there has been reworking and fragmentation within the biotope/lithotope
mid- to low-tidal sandy beaches with high opportunity for reworking, and high opportunity for storm concentration, with exogenic contribution from adjoining environments	*Donax faba, Dosinia incisa, Paphies* sp. and *Nassarius dorsatus* as the autochthonous components, and *Acrosterigma reeveanum, Anadara crebricostata, Anadara granosa, Cardita incrassata, Mimachlamys scabricostata, Oliva lignaria, Pinna bicolor, Septifer bilocularis, Solen kajiyamai, Spondylus wrightianus,* and *Trisidos tortuosa* as the exogenic (or allochthonous) components	some of these shells represent an autochthonous accumulation, though there has been reworking and fragmentation within the biotope/lithotope, but the majority have been transported to the lithotope from other environments
rocky shores (either Mesozoic bedrock, Tertiary age ironstone, Pleistocene limestones, or Holocene limestones, and Holocene beachrock)	*Arca ventricosa, Barbatia foliata, Chama reflexa, Conus textile, Conus victoriae, Cronia aurantiaca, Cypraea gracilis, Cypraea pyriformis, Herpetopoma atrata, Nerita undata, Planaxis sulcatus, Saccostrea cucullata, Septifer bilocularis, Spondylus wrightianus, Trochus maculatus* and *Turbo bruneus*	these shells signal derivation from rocky shores; in some instances where there are no outcrops of Mesozoic rocks or Pleistocene limestone at the shore, their appearance within the stratigraphic record indicates that limestone has formed along the coast (*e.g.*, headland dune barriers have become lithified to form calcarenites exposed at the coast), or beachrock has formed and is providing a rocky substrate; these shells make their appearance in the Cable Beach Sand, Port Smith Sand, and Eighty Mile Beach Coquina
zone of flotsam and jetsam at the high tide mark, where there is an accumulation of floating mollusc tests, *i.e., Spirula spirula,* and various species of *Sepia*	*Sepia* spp and *Spirula spirula*	these shells have been transported to the lithotope from oceanic pelagic environments

Table 13 (cont.)

Environment (habitat)	Main, diagnostic, or conspicuous molluscs	Comments
spits and cheniers where there is concentration of shells during storms	*Anadara secticostata, Asaphis violascens, Cantharus* cf. *erythrostoma, Cerithidea anticipata, Cerithidea cingulata, Certhidea obtusa, Chicoreus cornucervi, Cymatium waterhousei, Dosinia deshayesii, Dosinia incisa, Epitonium imperialis, Gafrarium dispar, Littoraria* cf. *cingulata, Mactra incarnata, Nassarius dorsatus, Nerita squamulata, Nerita undata, Neritina* cf. *violacea, Paphia crassisula, Phalium areola, Polinices* sp., *Saccostrea cucullata, Stramonita javanica, Tellina* cf. *piratica, Turbo laminiferus*	these shells appear to have several provenances – as the dominant components are small shells that are unlikely to have been food sources for the Indigenous people earlier in the Holocene (*e.g., Cantharus* cf. *erythrostoma, Cerithidea anticipata, Cerithidea cingulata*), they most likely have been transported to the lithotope by storms/waves, deriving from mangrove environments, low tidal sand flats, low tidal mud flats, and rocky shores (this matter is discussed later in the paper)
spits and cheniers with veneer of middens, where Indigenous people have concentrated particular species – the focus here is on the veneer of middens	*Anadara crebricostata, Anadara granosa, Saccostrea cucullata, Terebralia palustris,* and *Telescopium telescopium*	while the underlying gravel and sandy gravel of the spit or chenier may be composed of small shells as noted above, the surface veneer is composed of larger shells that were food items for the Indigenous people earlier in the Holocene (this matter is discussed later in the paper)
deflation hollows, or surfaces of coastal dunes, with middens, where Indigenous people have concentrated particular species	*Anadara crebricostata, Anadara granosa, Arca avellana, Barbatia coma, Barbatia foliata, Melo amphora, Modiolus auriculatus, Modiolus micropterus, Modiolus* cf. *trailii, Pinctada maxima, Saccostrea cucullata, Telescopium telescopium* and *Terebralia palustris*	large shells that were food items for the Indigenous people earlier in the Holocene, as well as molluscs that were utilitarian (*viz., Melo amphora*); located in upper supratidal environments and distant from the shore, these shells unequivocally indicate anthropogenic transport and highlight the shells that were food or tool items in the region

Formation would be a midden). However, there are problems where the middens occur on cheniers, because in these situations natural sedimentary processes as well as anthropogenic processes can aggregate such shells. Natural sedimentary accumulations of shells thus can grade into or overlap with middens. For instance, gravel beds of *Saccostrea cucullata* can be a storm deposit (Figure 7C from chenier 4 of the Race Course Plains Coquina), or a midden (Figure 11C of a midden from Camp Inlet), and in some circumstances, the gravel bed of natural sedimentary deposits of oysters can form the location where the oysters were consumed, thus mixing sedimentary deposits and middens.

The geomorphic form, and geographic occurrence relative to the shore suggests that many cheniers in the study area are wave-built deposits (as discussed above; also see Chappell & Grindrod 1984 and Lees 1992), but the geomorphic attributes of a chenier are not evidence to separate natural and anthropogenic processes of shell deposition. While many cheniers by their orientation and geometry may accord with the notion that they have been formed by cyclones, storms or high waves, once emergent above the high tide mark, they can be the site for human activity (a point discussed by Sullivan & O'Connor 1993). In this paper, cheniers that have mixed shell content, but where there is a proportion of small shells and shell fragments (e.g., grit-sized small gastropods), are assigned to a category of having sedimentary cores, and midden veneers. The size range of gastropods within the shell gravel has been a critical factor in deciding how to classify the deposit, in that if there is an abundance of small neritids and littorinids and comminuted oysters mixed with large bodies mollusc shells, it is unlikely that the former were a major food item but have been wave deposited. Bird *et al.* (2002), however, show that in modern Indigenous societies in Northern Australia, even *Asaphis violascens* occurring on sand patches on rocky shores, and rocky shore neritids could be harvested taking the size range of food items that can be harvested down to centimetre-scale. The criterion of the size of molluscs needs to be used with caution, and in conjunction with other sedimentologic information.

Interpreting the biostratigraphy: fossil assemblages in relation to stratigraphy

The stratigraphic units of the Canning Coast present a range of fossil and subfossil preservation types. Molluscan fauna diagnostic of the various Formations are illustrated in Figures 35–37. As noted in the section on Methods, the most abundant five (or ten) species of molluscs from a stratigraphic unit were selected for illustration to biostratigraphically characterise a Formation. The full list of molluscs present in any of the stratigraphic units has been provided in the formal descriptions of the Formations and Members.

Figure 35 shows the assemblages from the Lagrange Calcilutite Member, the Crab Creek Calcilutite Member, the Cable Beach Sand, the Willie Creek Calcarenite, the Kennedys Cottage Limestone, and the Race Course Plains Coquina underlying a chenier. The assemblages in the Lagrange Calcilutite Member and the Crab Creek Calcilutite Member are autochthonous biocoenoses, and faunally diagnostic of these units. The main fauna in the middle to lower Cable Beach Sand is an autochthonous biocoenosis, while the upper part (involving the cephalopod skeletons) is an allochthonous partial biocoenosis. The Kennedys Cottage Limestone, the earlier

Table 14

Summary of the molluscan content of the Formations and members in terms of their classification as fossils, and their autochthony or allochthony

Stratigraphic unit	Mollusc content	Classification
Shoonta Hill Sand (wind lags)	*Donax faba* and *Sepia* spp	all shells allochthonous, therefore allochthonous thanatocoenosis
Shoonta Hill Sand (midden)	*Melo amphora, Saccostrea cucullata, Telescopium telescopium, Terebralia palustris,* and *Anadara granosa*	all shells allochthonous, therefore allochthonous thanatocoenosis
Eighty Mile Beach Coquina	bivalves *Acrosterigma reeveanum, Acrosterigma vlamingi, Anadara crebricostata, Anadara granosa, Antigona chemnitzii, Cardita incrassata, Chama reflexa, Chama* sp. 1, *Donax faba, Dosinia incisa, Eucrassatella pulchra, Hyotissa hyotis, Macoma praetexta, Mimachlamys scabricostata, Paphia semirugata, Paphies heterodon, Paphies striata, Pinna bicolor, Placamen gravescens, Placuna placenta, Saccostrea cucullata, Solen kajiyamai, Spondylus wrightianus, Tapes literatus, Tellina piratica, Trisidos semitorta, Trisidos tortuosa, Venus lamellaris,* and unidentified Pectinid, and an unidentified Venerid, and the gastropods *Bulla ampulla, Bulla guoyii, Chicoreus rubiginosus, Chicoreus ryosukei, Chicoreus* sp., *Cominella* cf. *lineolata, Conus textile, Conus trigonus, Cypraea pyriformis, Duplicaria duplicata, Ficus eospila, Fusinus colus, Herpetopoma atrata, Melo amphora, Murex macgillivrayi, Murex* cf. *acanthostephes, Nassarius dorsatus, Naticarius alapapiliones, Oliva lignaria, Planaxis sulcatus, Polinices conicus, Strombus campbelli, Terebralia palustris,* and an unidentified Trochid	all shells are allochthonous, therefore allochthonous thanatocoenosis
Cable Beach Sand (assemblage 1)	dominated by *Donax faba, Paphies* sp., *Nassarius dorsatus* and *Oliva lignaria*	shells still within biotope, therefore autochthonous biocoenosis
Cable Beach Sand (assemblage 2)	bivalves *Donax faba, Paphies* sp., and the gastropods *Nassarius dorsatus* and *Oliva lignaria*, but dominated by bivalves *Acrosterigma reeveanum, Anadara crebricostata, Anadara granosa, Cardita incrassata, Mimachlamys scabricostata,* and the gastropods *Oliva lignaria, Pinna bicolor, Septifer bilocularis, Solen kajiyamai, Spondylus wrightianus* and *Trisidos tortuosa*, and fragments of *Melo amphora*	largely exogenic, derived from a number of environments, and therefore allochthonous thanatocoenosis
Cable Beach Sand (assemblage 3)	*Donax faba, Sepia* spp and *Spirula spirula*	shells still within biotope, others are exogenic, therefore mixed biocoenosis/ thanatocoenosis
Cable Beach Sand (assemblage 4)	*Sepia* spp and *Spirula spirula*	shells exogenic, but partially reflect the life assemblage, therefore allochthonous partial biocoenosis
Port Smith Sand	bivalves *Anadara crebricostata, Anomalocardia squamosa, Antigona* cf. *chemnitzii, Antigona chemnitzii, Arca avellana, Arca ventricosa, Asaphis violascens, Asaphis* sp., *Austriella sordida, Barbatia coma, Callista impar, Cardita* cf. *preissii, Dosinia incisa, Dosinia scalaris, Exotica assimilis, Hemidonax arafurensis, Irus* sp., *Mactra abbreviata* cf. *meretriciformis, Mactra westralis, Meropesta nicobarica, Paphies striata, Placamen gravescens, Saccostrea cucullata, Septifer bilocularis, Sunetta perexcavata, Tellina rostrata, Trachycardium flavum,* and an unidentified Mesodesmatid, and the gastropods *Amalda elongata, Astraea rotularia, Calthalotia strigata, Cerithidea reidi, Chicoreus permestus, Conus victoriae, Cronia aurantiaca, Cymatium vespaceum, Cypraea gracilis, Nerita undata, Phalium areola, Phasianella australis, Pyrene varians, Pythia* cf. *scarabaeus, Strombus campbelli, Syrinx aruanus, Tectus fenestratus, Trochus maculatus,* and *Turbo bruneus.*	many shells autochthonous, but many also exogenic, therefore mixed biocoenosis/ thanatocoenosis

Sandfire Calcilutite (middle to upper part) – the Lagrange Calcilutite Member	bivalves *Dosinia* sp., *Pitar* sp, *Saccostrea cucullata, Venus lamellaris,* and the gastropods *Cassidula angulifera, Cerithidea anticipata, Cerithidea cingulata, Ellobium aurisjudae, Nerita undata, Telescopium telescopium, Terebralia palustris* and *Terebralia sulcata,* and remains of Teredinidae ("shipworm")	all shells still within lithotope, and therefore autochthonous biocoenosis
Sandfire Calcilutite (middle to lower part) – the Crab Creek Calcilutite Member	bivalves *Paphies striata, Tellina capsoides, Tellina piratica, Tellina* spp, and the gastropod *Nassarius dorsatus*	all shells still within lithotope, and therefore autochthonous biocoenosis
Race Course Plains Coquina (chenier 1)	bivalves *Anadara granosa, Anadara secticostata, Anadara crebricostata, Asaphis violascens, Dosinia deshayesii, Dosinia incisa, Gafrarium dispar, Mactra incarnata, Paphia crassisula,* and *Saccostrea cucullata,* and gastropods *Cantharus* cf. *erythrostoma, Cerithidea anticipata, Cerithidea* cf. *cingulata, Cerithidea cingulata, Chicoreus cornucervi, Cymatium waterhousei, Epitonium imperialis, Littoraria* cf. *cingulata, Nassarius dorsatus, Nerita squamulata, Neritina* cf. *violacea, Phalium areola, Polinices* sp., *Stramonita javanica, Terebralia palustris, Turbo laminiferus,* and unidentified Marginellids	all shells allochthonous, and of multiple sources therefore allochthonous thanatocoenosis
Race Course Plains Coquina (chenier 2)	bivalves *Anadara granosa, Dosinia incisa,* and *Tellina* cf. *piratica*	all shells allochthonous, therefore allochthonous thanatocoenosis
Race Course Plains Coquina (chenier 3)	bivalves *Anadara granosa, Dosinia incisa,* and *Saccostrea cucullata*	partially a midden; all shells allochthonous, therefore allochthonous thanatocoenosis
Race Course Plains Coquina (chenier 4)	*Saccostrea cucullata*	not a midden, but all shells exogenic, but partially reflect a life assemblage, therefore allochthonous partial biocoenosis
Cape Gourdon Formation	*Anadara granosa*	fully a midden; all shells allochthonous, therefore allochthonous thanatocoenosis
Barn Hill Formation	bivalves *Modiolus auriculatus, Modiolus micropterus, Modiolus* cf. *trailii,* and *Saccostrea cucullata*	fully a midden; all shells allochthonous, therefore allochthonous thanatocoenosis
Horsewater Soak Calcarenite	*Donax faba*	exogenic, derived from the beach environment, and therefore allochthonous partial biocoenosis
Kennedys Cottage Limestone	bivalves *Acrosterigma* cf. *fultoni, Anadara crebricostata, Anadara granosa, Anadara* sp., *Arca avellana, Asaphis violascens, Barbatia foliata, Callista impar, Donax faba, Donax* sp., *Dosinia* sp., *Fragum hemicardium, Gafrarium tumidum, Modiolus micropterus, Saccostrea cucullata,* and an unidentified Venerid, and the gastropod *Melo amphora*	exogenic from a number of environments (mainly low tidal sands), and therefore allochthonous thanatocoenosis
Willie Creek Calcarenite	bivalves *Acrosterigma fultoni, Acrosterigma vlamingi, Anadara crebricostata, Anomalocardia squamosa, Barbatia coma, Barbatia foliata, Callista impar, Donax faba, Donax* cf. *faba, Dosinia scalaris, Gafrarium tumidum, Saccostrea cucullata, Semele jukesii, Tellina virgata,* an unidentified Cardiid, and an unidentified Venerid, and the gastropods *Conus* sp. and *Strombus campbelli*	shells from a mixture of low tidal environments and rocky shores, therefore allochthonous thanatocoenosis
Christine Point Clay	bivalves *Pitar* sp., *Saccostrea cucullata,* and the gastropods *Ellobium aurisjudae* and *Cassidula angulifera*	all shells still within lithotope, and therefore autochthonous biocoenosis

Holocene equivalent to the Cable Beach Sand, is dominated by *Donax faba*, but also contains *Barbatia foliata* and *Anadara crebricostata*, which appear to be derived from outside the lithotope; hence the assemblage is a mixed biocoenosis/ thanatocoenosis. The Willie Creek Calcarenite is dominated by *Donax faba, Barbatia foliata* and *Conus* sp, species that are diagnostic of low tidal sand flats, and represent life assemblages of a low tidal sand flat (of which the Willie Creek Calcarenite is the earlier Holocene equivalent). However, the Formation also locally contains an abundance of *Saccostrea cucullata*, indicating that there were nearby rocky shores that supplied oyster shells to the sediment; the assemblage thus is a mixed biocoenosis/thanatocoenosis. The shell gravel deposit in the Race Course Plains Coquina in a chenier under Race Course Plains is a monomictic coquina, composed almost totally of wave-fragmented *Saccostrea cucullata*, (Figure 7C) and represents an allochthonous partial biocoenosis, with the oysters derived from the lithotope of the Lagrange Calcilutite Member and transported landward by storms to form the chenier.

Figure 36 shows the assemblages from the Eighty Mile Beach Coquina and the Port Smith Sand. The assemblage in the Eighty Mile Beach Coquina, a polymictic shell gravel, is an allochthonous thanatocoenosis. It is a concentration of shells derived by erosion of a number of biostratigraphic units, comprising shells from habitats of beach, low tidal sand flats, and low tidal muddy sand flats. While most of the shells have been transported into the depositional lithotope from low tidal areas or from stratigraphic units formed in the low tidal lithotope, some of the shells derive from rocky shores. The assemblage in the Port Smith Sand is largely an autochthonous biocoenosis, though there are some derivatives from mangrove environments, and rocky shores. Shells from further upslope, *i.e.*, from mangrove environments are lacking.

Figure 37 illustrates the range in composition of middens, and mixed naturally deposited shell gravel and midden, in the various stratigraphic units in the region. The deposits illustrate four types: (1) those representing monomictic coquinas where Indigenous people have accumulated generally a single species of mollusc (*e.g.*, in Church Hill Sand at Broome, and at site 1 of Figure 11C in the Shoonta Hill Sand at Camp Inlet); (2) those representing oligomictic coquinas where Indigenous people have accumulated generally two or several species of mollusc (middens in Barn Hill Formation at Barn Hill, and midden in one of the cheniers underlain by the Race Course Plains Coquina at Race Course Plains); (3) those representing polymictic coquinas where Indigenous people have accumulated many species of edible mollusc and other species that were utilitarian (midden in site 2 in Shoonta Hill Sand in a deflation hollow of a mobile dune at Camp Inlet) and; (4) shell aggregate representing a polymictic coquina where there is a mixture of wave/storm deposited shells (*i.e.*, the smaller gastropods derived from mangrove environments, and similar in origin to the shells in chenier 3 of the Race Course Plains Coquina in Figure 35) and anthropogenically accumulated shells such as *Anadara granosa* and *Saccostrea cucullata*.

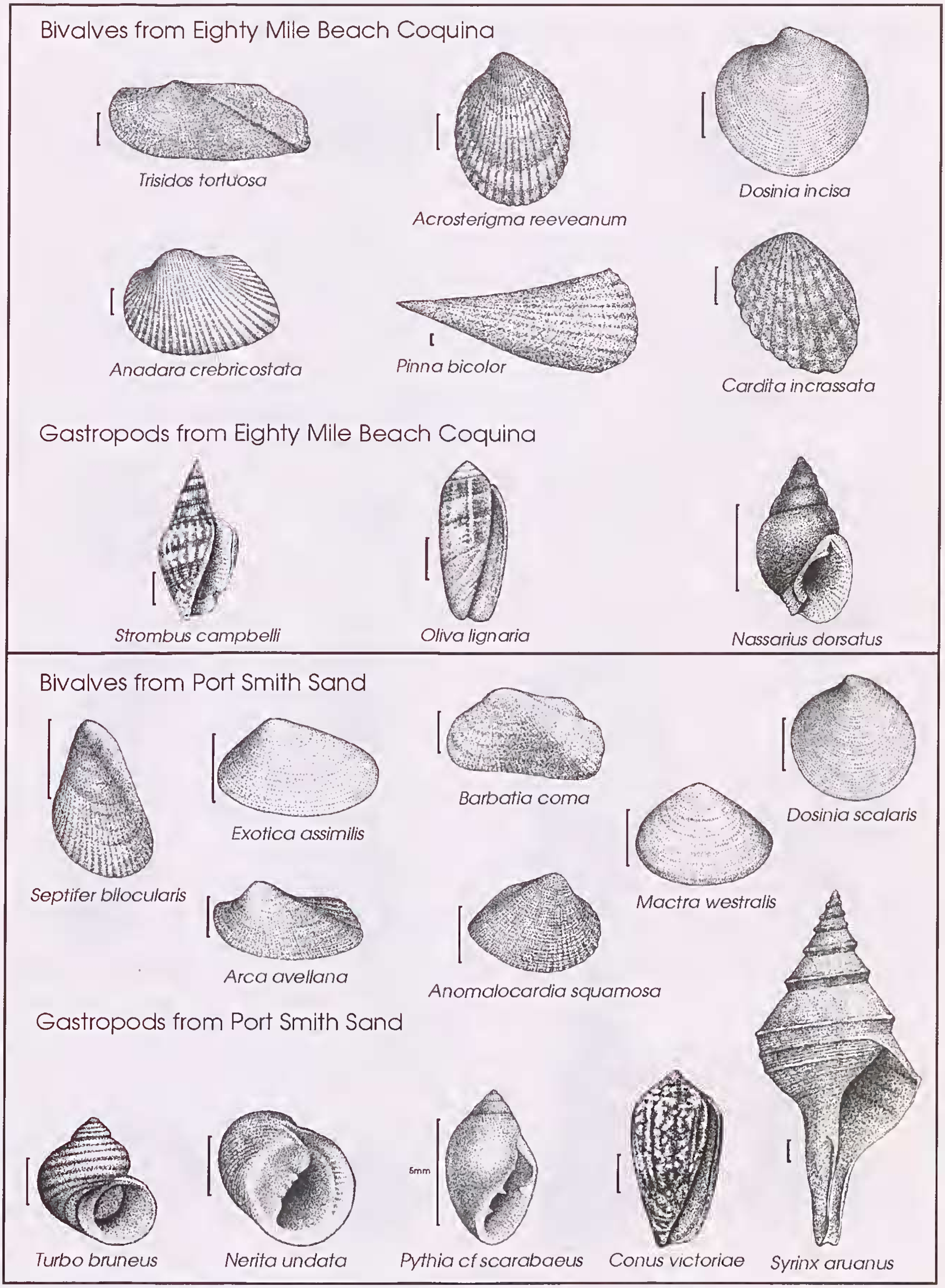
A comparison of two sets of environmentally equivalent Formations (*viz.*, Cable Beach Sand with the Kennedys Cottage Limestone, and the Port Smith Sand with the Willie Creek Calcarenite), separated by *circa* 5000 yrs in age, shows some differences.

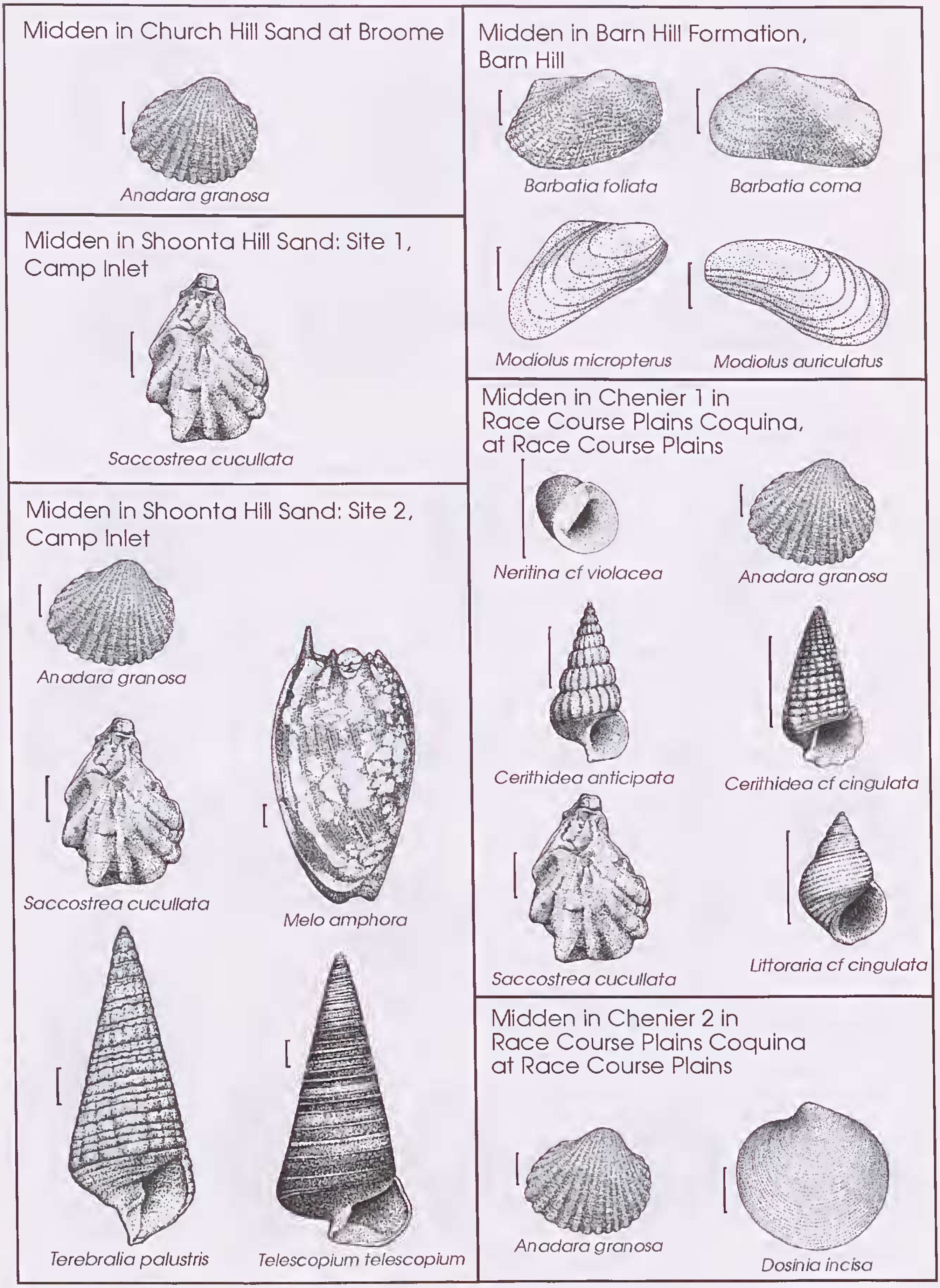
For the modern and earlier Holocene beach environments (the Cable Beach Sand with the Kennedys Cottage Limestone), the components of *in situ* molluscs such as *Donax faba* and *Donax* sp were common to both, but *Paphies* sp., *Nassarius dorsatus* and *Oliva lignaria*, present in modern environments, were not found in the older beach-deposited unit. This would imply that there have been subtle changes in mollusc assemblage composition from *circa* 5000 yrs BP to the present. However, since the two Formations are dominated by allochthonous thantocoenoses, there needs to be a comparisons of the exogenic components as well, as they can provide an index of the low tidal flat and along-shore assemblages. Here too, there are differences in mollusc assemblage composition, which also implies that there have been subtle changes in these assemblages from *circa* 5000 yrs BP to the present. Some of this may be regionally environmental, but some may be due to the changes that have occurred in the low tidal flat zone, the source of the exogenic shells.

For the modern and earlier Holocene low tidal sand flat environments (the Port Smith Sand with the Willie Creek Calcarenite), some components of *in situ* molluscs, such as *Anomalocardia squamosa, Barbatia coma, Barbatia foliata, Callista impar, Conus* sp., *Dosinia scalaris,* and *Strombus campbelli,* show that there are similarities,. However, there also are differences: the fauna in the Willie Creek Calcarenite is relatively depauperate compared to that in the Port Smith Sand, and many sand-dwelling species now occurring as fossils in the Willie Creek Calcarenite were not as ubiquitous as they are today in the Port Smith Sand. Further, there is a larger component of exogenic species in the Port Smith Sand, compared to the Willie Creek Calcarenite. For instance, there are more species deriving from rocky shores (*e.g., Conus victoriae, Saccostrea cucullata* and *Turbo bruneus*) and from muddy environments (*e.g., Paphies striata*). This implies firstly, that rocky shores have become more common and widespread since the earlier part of the Holocene (a factor to be discussed later), and secondly, that the modern low tidal flat environments are sedimentologically dynamic, switching from sand-dominated, to muddy sand to mud-veneered, with concomitant changes in mollusc assemblages. As a consequence, again, there appears to be a difference in the composition and abundance of the molluscan fauna in the two environmentally equivalent Formations between *circa* 5000 yrs BP and the present.

Within the Sandfire Calcilutite, it is usually not possible to compare earlier Holocene mangrove-derived molluscan assemblages with modern assemblages, as the former have generally been diagenetically modified to the extent that they are shell-depauperate. Where

Figure 36. Shell assemblages of the Eighty Mile Beach Coquina and Port Smith Sand. Bar scale is 1 cm. ▶


Bivalves from Eighty Mile Beach Coquina
Trisidos tortuosa
Acrosterigma reeveanum
Dosinia incisa
Anadara crebricostata
Pinna bicolor
Cardita incrassata
Gastropods from Eighty Mile Beach Coquina
Strombus campbelli
Oliva lignaria
Nassarius dorsatus
Bivalves from Port Smith Sand
Septifer bilocularis
Exotica assimilis
Barbatia coma
Dosinia scalaris
Mactra westralis
Arca avellana
Anomalocardia squamosa
Gastropods from Port Smith Sand
5mm
Turbo bruneus
Nerita undata
Pythia cf scarabaeus
Conus victoriae
Syrinx aruanus


Midden in Church Hill Sand at Broome
Anadara granosa
Midden in Shoonta Hill Sand: Site 1, Camp Inlet
Saccostrea cucullata
Midden in Shoonta Hill Sand: Site 2, Camp Inlet
Anadara granosa
Saccostrea cucullata
Melo amphora
Terebralia palustris
Telescopium telescopium
Midden in Barn Hill Formation, Barn Hill
Barbatia foliata
Barbatia coma
Modiolus micropterus
Modiolus auriculatus
Midden in Chenier 1 in Race Course Plains Coquina, at Race Course Plains
Neritina cf violacea
Anadara granosa
Cerithidea anticipata
Cerithidea cf cingulata
Saccostrea cucullata
Littoraria cf cingulata
Midden in Chenier 2 in Race Course Plains Coquina at Race Course Plains
Anadara granosa
Dosinia incisa

molluscs do still exist as fossils in the earlier mangrove environment lithotopes (*e.g.*, the Christine Point Clay), they are similar to assemblages in the modern environments. It also is usually not possible to compare earlier Holocene low-tidal mud flat tellinid-dominated molluscan assemblages with modern assemblages, as the former have generally been bioturbated to the extent that they are composed of shell fragments with scattered whole shells.

Shell gravels in the cheniers clearly have mixed origins, with derivation from mangrove environment lithotopes, low tidal flat lithotopes, or by accumulation as middens. Their composition at a site, however, gives indications as to the composition of shells in the low tidal flat at the time of their collection.

Middens provide other types of insight into variation of mollusc assemblages in the region. Many middens are monomictic, some are oligomictic, and others are polymictic, and a number of them show changes in mollusc assemblages that have occurred in the food-gathering sites. Similar to the shell gravel content of the cheniers, their composition at a site gives indication as to the composition of mollusc assemblage in the low tidal flat at the time of their harvesting, and changes in this composition in time. For instance, the middens dominated by *Anadara granosa* in the Broome area, in the Church Hill Sand, and in the Camp Inlet area also show that this species was significant on the low tidal flats. On the other hand, changes in tidal flat fauna are evident in the Barn Hill area, where at one time *Anadara granosa* was being harvested, and at another time, *Modiolus auriculatus*, *Modiolus micropterus*, *Modiolus* cf. *trailii*, and *Saccostrea cucullata* were being harvested.

The Eighty Mile Beach Coquina represents the most mixed sequence of shells, with its shell content indicating fauna that once inhabited sandy, muddy sand, mud, and rocky substrates. It is a shell concentrate derived by the reworking of *all* shell-bearing Formations. As such, a radiocarbon date obtained from this Formation was not concordant with the general younging of Formations towards the coast, and probably indicates derivation from older Holocene Formations reworked into shell lag.

The only Formation not well represented in the shell lags within the Eighty Mile Beach Coquina is the Sandfire Calcilutite. Where coastal erosion is reworking and concentrating shells from pre-existing Formations exposed at the coast, the middle to upper part of the Sandfire Calcilutite being shell-depauperate (as discussed above) will not yield many fossils, and the middle to lower part will yield tellinid fragments or entire tellinids that would fragment easily. In essence, reworking of the Sandfire Calcilutite will not yield many shells to the Eighty Mile Beach Coquina.

Exogenic shells can be used to indicate occurrences of rocky shores. If, for instance, there are no nearby rocky shores cut in Mesozoic, Tertiary or Pleistocene rock, then the appearance of a rocky shore fauna in the earlier Holocene sequences signals the appearance of rocky substrates, and most probably the formation of beachrock. In this case, beachrock, as in the modern environment, would be encrusted by oysters and grazed by neritids and littorinids, supplying these shells as fossils to the sediments. In the younger Holocene sequences, the appearance of a rocky shore fauna as exogenic fossils points to the formation of beachrock and/ or to the induration of earlier Holocene barriers into calcarenites that would function as rocky shores.

As mentioned above, modern low tidal flat environments can be sedimentologically dynamic, switching from sand-dominated, to muddy sand to mud-veneered, with concomitant changes in mollusc assemblages. For instance, the substrate in front of the eroding shore along Eighty Mile Beach and the low tidal sand flats in Port Smith varies spatially and temporally from mobile, medium/coarse brown relatively oxygenated sand, to shell gravel, to relatively anoxic grey sand (Figure 22F), to less anoxic grey sand (Figure 26), to a muddy sand veneer on shell gravel to shell gravel to medium/coarse sand (Figure 27). The low tidal flats underlain by carbonate mud may be thixotropic, or after a storm, or wave winnowing, a shell fragment veneered mud surface. Species of molluscs that are adapted to specific substrate types in terms of sand grainsize, mud content, oxygenation, and sediment mobility would be eliminated or favoured to inhabit these types of substrates as they changed. With spatially and temporally changing substrates, mollusc assemblages would change from sand-dominated to muddy sand types, to mud-dominated, and with later mixing by tides, waves, and bioturbation, ultimately to be preserved as an environmentally mixed group. It would appear that earlier in the Holocene under conditions of sustained accretion and progradation, that there was little opportunity for such ecological changes, and for reworking and mixing.

Thus, the composition of the fauna can signal that there have been changes in substrates, and this is particularly important as the rate or dynamics of substrate changes will influence the rate or dynamics of assemblage changes. The regional stratigraphy points to alternating erosion and deposition and for major changes in low tidal substrates from sand, to muddy sand to mud (see later), and hence it can be expected that there would have been changes in the mollusc assemblages. This is reflected somewhat in the thanatocoenoses of shells on beaches and particularly in the extreme mixtures of shells within the thanatocoenoses of the Eighty Mile Beach Coquina.

History of coastal sedimentation and palaeogeography of the Canning Coast during the Holocene

A number of sites were selected where detailed study was undertaken into the geomorphology and stratigraphy of the Canning Coast (Figure 3A). A brief description and interpretation in terms of coastal form, framework stratigraphy, Holocene stratigraphy,

◀ **Figure 37.** Shell assemblages from various middens from various formations. Bar scale is 1 cm.

radiocarbon ages (if relevant), and coastal history of the study sites is provided in Table 15, based on the relevant information in Figures 10–34. This synthesises all the geomorphic, stratigraphic, and radiocarbon information and summarises the significant points of each of the study areas.

From an overall perspective, there are two main depositional regimes along the Canning Coast: one is high-energy, sand-dominated, the other is low energy, mud-dominated. For both there is a general similarity in lithology and stratigraphic sequences between modern coastal depositional systems and that of the earlier Holocene systems.

Along the modern coast, sand accumulates in the higher energy environments, developing a shoaling sequence of lithologically and biostratigraphically distinct sediments from low tidal flat sand, beach sand, beachrock, storm-deposited boulder, cobble and pebble beds, and calcareous coastal dunes as represented by the Port Smith Sand, Cable Beach Sand, Cape Boileau Calcarenite Member, Lombadina Conglomerate Member, and the Shoonta Hill Sand, respectively, that provide direct analogues for their earlier Holocene lithified counterparts such as Willie Creek Calcarenite, Kennedys Cottage Limestone, and Horsewater Soak Calcarenite. The only significant lithological differences between the modern sand-dominated Formations and their earlier Holocene equivalents is that the latter are generally lithified and have formed with MSL 2 m to 1.5 m higher than present. As a result, there are two age-structure groups for high-energy sediment accumulations in this region: those that are now calcarenitic, and generally > 3000 years old, formed under conditions of a higher sea level; and the unconsolidated sediments of Port Smith Sand, Cable Beach Sand and Shoonta Hill Sand which are relatively young Holocene Formations, *i.e.*, generally < 3000 yrs old.

Carbonate mud accumulates in protected environments, and within both the mid-tidal to upper-tidal zone and the mid-tidal to lower-tidal zone, initially, it is lithologically distinct, but in time through diagenesis it may become more homogeneous. The modern processes and products of the lithotope of the Sandfire Calcilutite (and its Members) are useful for interpreting earlier Holocene sequences of this Formation, particularly when mangrove stumps, mangrove wood fragments, and associated molluscs, or tellinid-bearing laminated structures are still preserved. Along deeply indented coasts, and hence reasonably well protected from direct wave action, carbonate mud has accumulated from the onset of the post-glacial transgression, and formed prograding coastal plains. The transition from earlier Holocene carbonate mud accumulation to the modern depositional environments along the length of prograded plains is continuous, and hence the lithological analogue for the older parts of the mud deposits is direct. Apart from deeply indented embayments, and the larger examples of discrete embayments, where carbonate mud began accumulating immediately after the peak of the marine transgression, the Sandfire Calcilutite is relatively young, *i.e.*, generally < 3000 yrs old, as it mostly came to be formed after sea level fell to a height that the calcarenitic ridges could more effectively act as barriers to the small discrete embayments where carbonate mud could accumulate.

Variations on the two sedimentary patterns, described above, were developed as a consequence of (1) a falling sea level, (2) progradation of carbonate mud to form coastal plains, and coastal plain accretion advanced to the point that its seafront became more exposed to prevailing wave attack, and (3) the seafront of the coastal plain developed a new stratigraphic unit reflecting the more recent history of coastal erosion.

In the first instance, with a higher sea level, it appears that wave energy entering the smaller discrete embayments was more pervasive, hence many embayments were sand-dominated; some even had sandy ridges (later to be lithified into calcarenite ridges) formed along their inner shores. But with the build-up of sand ridges (later to be lithified), and concomitant fall of sea level, the embayment-head barriers could act more effectively to protect inner parts of the embayments, and carbonate mud began accumulating interior to a given embayment. The commencement of carbonate mud accumulation in the smaller embayments generally coincided with the fall in sea level beginning about 3000 yrs BP. Consequently, thereafter, carbonate mud began to accumulate in those embayments protected by calcarenite barriers. Thus, sedimentation associated with the embayment switched from sand-dominated under conditions of a higher sea level to mud-dominated under conditions of a lower sea level.

Headland spits and small barriers also developed at the "headlands", or mouths, of the larger deeply indented embayments and funnel-shaped embayments, such as Roebuck Bay and the Salt Creek embayment, but they were not large enough to afford these larger embayments as much shelter as occurred in the smaller embayments.

In the second instance, with a falling sea level, and with the progressive filling of the once deeply indented embayments by progradation to form coastal plains, the seafront advanced from being relatively protected in an indented embayment to being more openly exposed. On muddy tidal flats, such as in the Salt Creek funnel-shaped embayment, the progression to a more consistent exposure to wave attack resulted in alternating coastal advance and retreat, reflected as periods of mud accretion alternating with periodic development of barriers and cheniers. This type of coastal activity increased in frequency towards the present as the edge of the coast progressed closer to its present position.

Thirdly, in areas that are not definitively protected by calcarenite barriers, with coastal retreat becoming more frequent, there was much reworking of early (shelly) Formations. A new unit, the Eighty Mile Beach Coquina, composed of shell concentrate representing the winnowed deposit of eroded Formations, was developed. Thus, the more recent history of the Canning Coast has seen marked and widespread erosion, so that the stratigraphic products of coastal erosion have become common (*viz.*, the Eighty Mile Beach Coquina)

The history of sedimentation and geomorphic changes over the period 7000 yrs BP to the present is diagrammatically illustrated in Figures 37 and 38 for discrete small embayments and for large, funnel-shaped, deeply indented embayments.

The Holocene palaeogeography of the Canning Coast is summarised in four stages in Figure 40. Figure 40 should be viewed in conjunction with Figures 38 and 39, as the latter two provide details of the palaeogeographic changes that were taking place at the smaller scale. Radiometrically, in this study, the history of Holocene coastal sedimentation begins at *circa* 7500 yrs BP.

The post-glacial marine transgression, when sea level reached its maximum height, essentially flooded into the western margin of the Great Sandy Desert. The shape of the coast at that time when there was as yet no Holocene sedimentary filling of basins, reflected hinterland geology and geomorphology. There were numerous embayments, and from a large scale perspective, the coastline was jagged and locally rocky (Figure 40A). Three types of shore were present at the time: large funnel-shaped embayments; small embayments located between rocky headlands; and that of rocks and desert dunes exposed at the coast.

The initial control of the sedimentation patterns in the Holocene, some 7500 yrs ago, after the incursion by the sea were firstly, the deep embayments that were lowlands and valley tracts, secondly, the ridges of Mesozoic rock (*i.e.*, the Dampier Peninsula, and the western extension of the Edgar Range), and thirdly, the relict occurrences of Pleistocene limestone ridges. The deep embayments determined the sites of accumulation of carbonate mud, and the headlands of the jagged coast determined the development of barrier-barred small embayments. Between 7000 yrs BP and *circa* 5000 yrs BP, the coastline consisted of deeply indented embayments partly filled with carbonate mud to form coastal plains, and a barrier, spit and dune dominated coast where barriers, spits and dunes were developed from the headlands jutting out to sea. Figure 40B illustrates the coast at this time – a system dominated by barriers, with MSL 2 m higher than present, and local pockets of carbonate mud.

When sea level began to fall from 1.5 m to the present level, the sand ridges (later to become calcarenite ridges) became barriers to the small embayments, and with a lower MSL, there was less wave penetration into the embayments. The result was that carbonate mud began to accumulate around the periphery of the embayments eventually filling them (Figure 38). The bay-head environment is the site where fluvial discharge from small creeks delivers kaolinitic mud and quartz sand to build high-tidal to supratidal alluvial fans (*cf.* Semeniuk 1985). The fall in sea level also appeared to accelerate the filling and progradation of the deeply indented embayments. Figure 40C illustrates the coast *circa* 3000–2000 yrs BP, with coastal plain accretion to a position further offshore than it is at present. The change from sandy barriers to calcarenite barriers also created rocky shore environments in front of many embayments, with the concomitant influx of rocky shore molluscan fauna into the fossil and subfossil record.

The present coast shows the following two main features (Figure 40D): (1) generally along the exposed mud-filled embayments where they are not protected by calcarenite barriers, there is widespread coastal erosion and retreat with development of frontal barrier dunes (Figures 25–27); and (2) there also is moderate coastal retreat in front of the small embayments that are barricaded by calcarenite ridges where such ridges are plastered onto pre-existing rocky headlands that still jut out to sea. Locally, where there are calcarenite ridges parallel to the shore exposed at the coast, there has been some retardation of coastal retreat. Erosion has proceeded *via* two processes: that of wave attack that has eroded the calcarenite barriers as well as exposed seafronts of calcilutite, and that of tidal creek erosion that has incised into the mud flats between MSL and HAT (see Semeniuk 1981b for description of such erosion in nearby King Sound). The massive erosion of the seafront of mud-dominated large embayments has developed broadly curving coastal forms.

The extensive erosion of the seafront of coastal plains, and the reworking of extant shelly Formations has resulted in the development of the Eighty Mile Beach Coquina, which is essentially a "signature Formation" of this phase of the Holocene coastal history, reflecting coastal erosion. Extensive erosion of mud flats by tidal creeks and wave attack also has released and remobilised massive volumes of carbonate mud into the environment. The results of erosion of the mud are two-fold. Firstly, there is a flux of mud into the environment, often where it is not normally deposited, thus altering the grainsize properties of substrates at the local scale and on a short term basis, with attendant effects on habitat characteristics, and invertebrate faunal composition, and hence on changes to tidal flat ecosystem characteristics. Secondly, there is local accumulation of carbonate mud in mid- to low-tidal areas and into ebb-flood delta fans of tidal creeks. For instance, currently, the seafront of Roebuck Bay is eroding, and concomitantly, the seaward margin of Roebuck Plains is being massively incised by extensive tidal creek erosion. The export of the erosion products (the fine-grained mud) is voluminous and is deposited onto the mid- to low-tidal flats of Roebuck Bay which, regionally, is still relatively a protected embayment. Hence, mid to low tidal flats of Roebuck bay are underlain by thick carbonate mud deposits. In contrast, the erosion of carbonate mud deposits along the seafront of Eighty Mile Beach, in a strong wave dominated environment, results in a general export of the mud, although there is local accumulation in the short term.

The history of sedimentation, the stratigraphy, biostratigraphy, and radiocarbon dates in the region provide clues to a number of inter-related features of the area over the Holocene. These are discussed in terms of the ubiquitous rise and fall of sea level, the occurrence of ooids and beach rock (and its derivatives) throughout the Holocene, subaerial cementation of sand dunes, and the diversity of midden composition.

It appears that the post-glacial rise in sea level to a position 2 m above the present, and then its falling to 1.5 m and to present levels, is a region-wide event. All calcarenite barriers that bar small embayments appear to have been formed 7000–3000 yrs BP, when sea level was higher. The response to a falling sea level within the smaller embayments, *i.e.*, accumulation of mud therein, also appears to be a region-wide event. While the rise and fall of sea level may have been ubiquitous and synchronous throughout the region, there was a differential response to a falling sea level, as described above, with deeply indented embayments changing from

Table 15

Interpretation of key features of the various study area shown in Figure 3A

Site	Coastal form, framework stratigraphy, Holocene stratigraphy	Key geomorphic and stratigraphic features and coastal history
1. Cape Leveque and Lombadina area	rocky and sandy shore coast cut into Mesozoic rocks, Tertiary rocks, Pleistocene limestone and Pleistocene red dune sand; Holocene stratigraphy consists of Cable Beach Sand, Cape Boileau Calcarenite Member, Lombadina Conglomerate Member; Shoonta Hill Sand, Sandfire Calcilutite, Barn Hill Formation, Cape Gourdon Formation, and Church Hill Sand	Cable Beach Sand, with well developed Cape Boileau Calcarenite Member and Lombadina Conglomerate Member; retreating Shoonta Hill Sand; well developed Barn Hill Formation, Cape Gourdon Formation, and locally, Church Hill Sand; retreat of coast with dunes retrograding over embayments, and exposure of ridges of Pleistocene limestone
2. Beagle Bay; central part of embayment	funnel-shaped embayment, with prominent creek draining into the bay head; embayment cut into Mesozoic rocks and Pleistocene red dune sand; Holocene stratigraphy consists of Christine Point Clay, Sandfire Calcilutite	Christine Point Clay developed along axis of bay head; later channel cut into the Formation and overlain by Sandfire Calcilutite; date of 5310 yrs BP for the upper part of the Christine Point Clay; head of bay filling with Christine Point Clay, and main embayment filling with Sandfire Calcilutite
3. Camp Inlet	lobate embayment cut into Mesozoic rocks and Pleistocene red dune sand; Holocene stratigraphy consists of Willie Creek Calcarenite, Kennedys Cottage Limestone, Christine Point Clay, Shoonta Hill Sand	complex stratigraphy of earlier Holocene units formed ~ 1.5 m above present MSL, incised by channels filled with Christine Point Clay and Sandfire Calcilutite; coast is now markedly retrograding; shoaling of basal part of the channel filled with Christine Point Clay took place between *circa* 2400 (- 2600) yrs BP and 1800 yrs BP; soil within Shoonta Hill Sand, signalling relatively more humid conditions, approximately same age as the clay filling of the channel with Christine Point Clay; oyster middens in the soil within the Shoonta Hill Sand; Kennedys Cottage Limestone is absent, replaced by a structureless to bioturbated shelly sand
4. Cape Boileau and 5. Willie Creek	Cape Boileau to Willie Creek is part of a single large complex of a shore-parallel lagoon, narrow to the north, and broad to the south (and with multiple scalloped margins); the entire lagoon barred by Holocene calcarenite and modern dunes; the northern end at Cape Boileau has a remnant Pleistocene limestone barrier ridge; hinterland of Pleistocene red dune sand; Holocene Formations and members include Willie Creek Calcarenite, Kennedys Cottage Limestone, Horsewater Soak Calcarenite, Sandfire Calcilutite, the Djugun Member, and Shoonta Hill Sand	Cape Boileau is the location where beachrock is plastered onto a Pleistocene limestone ridge; this location has been a barrier and lagoon system since the early part of the Holocene; the Holocene barrier extends south to the Willie Creek embayment; the earlier Holocene barrier that extends from Willie Creek to Cape Boileau is comprised of shoaling stratigraphy, formed with MSL 2 m higher than present, of earlier Holocene low-tidal sands to beach sands, to aeolian sands; with development of beachrock and storm conglomerates (all now lithified); barrier protects the embayment where Sandfire Calcilutite has accumulated; the eastern margin of the Willie Creek embayment also illustrates the type of stratigraphic sequence that forms where there is fluvial discharge from small bay-head creeks that build high-tidal to supratidal alluvial fans (see Transect A–B in Figure 12)
6. Coconut Well embayment and 7. Cable Beach area	this system also is a single large complex, with a shore-parallel lagoon, narrow to the north, and broad to the south (with multiple scalloped margins); the entire system largely barred by Holocene calcarenite; the northern linear lagoon sheltered partly by a barrier ridge of Holocene calcarenite (Horsewater Soak Calcarenite) and modern dune (Shoonta Hill Sand); landward shoreline bordered by Kennedys Cottage Limestone and Horsewater Soak Calcarenite; hinterland of Pleistocene red dune sand; northern lagoon leeward of the barrier has a meandering outlet, and is filled with Sandfire Calcilutite and bioturbated sand in different parts of the lagoon; in the Cable Beach area, the broader lagoon is barred by a ridge of Holocene calcarenite and modern dune; hinterland of Pleistocene red dune sand; lagoon leeward of the barrier is filled with Sandfire Calcilutite; hinterland of Pleistocene red dune sand	at Coconut Well, to seaward, there is a barrier with shoaling stratigraphy of Cable Beach Sand and Shoonta Hill Sand formed with MSL at present position, abutting against Holocene calcarenites and modern dune sands; the linear lagoon, with its barriers, and meandering outlet, provides a model for the channelling and sedimentary in-filling evident in Holocene sequences such as at Camp Inlet, and show the dynamism of the coast of cut-and-fill and migration of barriers along the shore (*i.e.*, shore-parallel elongating spits); in the Cable Beach area there is a shoaling stratigraphy of Cable Beach Sand with MSL at present position, abutting against Kennedys Cottage Limestone and Horsewater Soak Calcarenite formed with MSL 2 m higher than present, showing juxtaposition of two coastal sand units formed at different heights of MSL; radiocarbon dates show that MSL reached its present position at about 2100 yrs BP; the shoreline bordered by Kennedys Cottage Limestone shows that the open embayment originally was high-energy beach environment capped by dunes

8. Dampier Creek	u-shaped embayment filled with Sandfire Calcilutite; hinterland of Pleistocene red dune sand; mouth of embayment with small partial barrier of spits/dunes	Sandfire Calcilutite formed with MSL 2 m above present, falling to 1.5 m above present about 3400 yrs BP; barrier of sand with middens at 3600 yrs BP; a remnant of a crust at a level of HAT formed on Sandfire Calcilutite; the remnant crust shows induration of Sandfire Calcilutite took place at modern HAT, and there has been subsequent erosion of the embayment by tidal creeks extending landwards (*i.e.*, the Dampier Creek embayment is currently being emptied of mud content)
9. Crab Creek and 10. Roebuck Plains	long u-shaped to funnel-shaped embayment filled with Sandfire Calcilutite; hinterland of Pleistocene red dune sand; mouth of embayment with small barrier spits/dunes to the north and a complex of headland barriers, spits and cheniers to the south	the second largest mud-filled embayment in the region; the deeply indented embayment, protected from direct wave action, has progressively filled with Sandfire Calcilutite; muddy tidal flat deposits of this Formation onlap red sand linear dunes along the eastern, north-eastern, and southern margins (similar to tidal flat sediments burying red sand linear dunes in King Sound; see Jennings [1975] and Semeniuk [1980]); currently, seaward edge of the Roebuck Plains embayment is undergoing massive erosion by tidal creeks extending from MSL to HAT; these erosional circumstances generate voluminous amounts of mud which is deposited to form extensive low tidal mud flats; radiocarbon ages show that the embayment was already half-filled at about 5000 yrs BP, with MSL 2 m above present; there is a northern occurrence of Race Course Plains Coquina, within which there is a two layered shell sequence: an older 2350 yrs BP oyster midden and a younger 1285 yrs BP *Anadara* midden
11. Thangoo	broad u-shaped embayment, between "headlands" of Pleistocene red dune sand, filled with Sandfire Calcilutite; spits and dunes emanate from headlands; the prograded coast plain locally has cheniers (Race Course Plains Coquina)	this area illustrates prograded muddy coastal plain (underlain by Sandfire Calcilutite) along the southern margin of Roebuck Plains and the interactions with headlands of red dune sand, the development of cheniers, and the stratigraphic relations that develop in these coastal settings, *e.g.*, the cheniers are perched on the prograded muddy tidal flat sediments
12. Race Course Plains	very broad u-shaped embayment, between "headlands" of Pleistocene red dune sand, filled with Sandfire Calcilutite; the southernmost part of Roebuck Plains sedimentary complex; dominance of cheniers (Race Course Plains Coquina)	this area illustrates prograded muddy coastal plain (underlain by Sandfire Calcilutite), with a predominance of cheniers, and the stratigraphic relations that develop in these coastal settings, *e.g.*, the cheniers are perched on the prograded muddy tidal flat sediments
13. Barn Hill and Church Hill (and the Cape Gourdon area)	coastal tract with outcrop of Mesozoic sedimentary rock, as an extension of the Edgar Range, with Pleistocene red dune sand also at the coast; Holocene Formations include the Cape Gourdon Formation, the Barn Hill Formation, the Church Hill Sand, the Shoonta Hill Sand, and locally, the Cable Beach Sand	coastal processes acting on outcrops of Mesozoic rocks and Pleistocene red dune sand result in various stratigraphic relationships; there are coastal alluvial fan sedimentation (alluvial fans interdigitating with beach sands and dunes); there are interactions of red sand and coastal dunes (and development of limestone lenses in red sand, and carbonate laminae and beds in bedded/laminated red sand, and perching of coastal calcareous dunes); and there are coastally reworked red sand; these Formations are well represented as the Cape Gourdon Formation, Barn Hill Formation, the Church Hill Sand, the Shoonta Hill Sand; these Formations and their stratigraphic relationships provide a valuable model of Pleistocene red dune sands interacting with coastal processes
14. Port Smith	shore-parallel linear embayment with Holocene calcarenites forming a shore-bordering unit as well as a barrier system; hinterland of Pleistocene limestone and Pleistocene red dune sand; Holocene Formations and members include Willie Creek Calcarenite, Kennedys Cottage Limestone, Horsewater Soak Calcarenite, Sandfire Calcilutite and the Port Smith Sand	the earlier Holocene calcarenites forming a shore-bordering ridge and a barrier show that the embayment was mud-free earlier in the Holocene; the calcarenites exhibit shoaling stratigraphy of low-tidal sands to beach sands, to aeolian sands; with development of beachrock and storm conglomerates (all now lithified), when MSL was 2 m higher; the present sedimentation patterns, with MSL at its present position, there is shore-hugging Sandfire Calcilutite, and a central basin of Port Smith Sand

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Table 15 (cont.)

Site	Coastal form, framework stratigraphy, Holocene stratigraphy	Key geomorphic and stratigraphic features and coastal history
15. Lagrange Bay (embayment) and Cowan Creek	Lagrange Bay is a u-shaped embayment with multiple scalloped margins; Cowan Creek is a broad u-shaped embayment with two scalloped margins; both have a hinterland of Pleistocene red dune sand and a barrier of Holocene calcarenite; Pleistocene limestone is also present locally in the sequence; Holocene Formations and members include Willie Creek Calcarenite, Kennedys Cottage Limestone, Horsewater Soak Calcarenite, Sandfire Calcilutite and the Djugun Member	shoaling stratigraphy of earlier Holocene low-tidal sands to beach sands, to aeolian sands; with development of beachrock and storm conglomerates (all now lithified) was developed with MSL 2 m higher than present; barrier now protects the embayment where Sandfire Calcilutite has accumulated; Sandfire Calcilutite began deposition in both bays when sea level fell to 1.5 m above the present (there is evidence of the initiation of carbonate mud accumulation where it on-lapped the red dune sands *circa* 3200 yrs BP); freshwater discharge along interface of red dune sand and tidal flat has cemented the mud
16. Cape Bossut area	linear Pleistocene limestone ridge barring a small embayment that is underlain by Sandfire Calcilutite; Pleistocene limestone is overlain by a palaeosol, and in turn by Cape Boileau Calcarenite member; Shoonta Hill Sand perched on top of seacliff	this area shows the nature of the Pleistocene limestone, and the mud-filled embayment that accumulates to leeward of the limestone ridge
17. Frazier Downs embayment	Frazier Downs embayment is u-shaped with multiple scalloped margins; it has a barrier of Pleistocene limestone overlain by Holocene calcarenite (Horsewater Soak Calcarenite) and Holocene beach ridges (Shoonta Hill Sand); hinterland of Pleistocene red dune sand; a variety of Pleistocene limestones, and a Pleistocene unit of red sand with limestone lenses present locally in the sequence; Holocene Formations and members include Kennedys Cottage Limestone, Horsewater Soak Calcarenite, Sandfire Calcilutite and the Djugun Member	this system, cradled between (buried) Mesozoic rock headlands, has been an embayment with barriers since the Pleistocene; currently is largely barred by Holocene calcarenites (a shoaling system formed with MSL 2 m higher than present) and Holocene beach ridges; its southern entrance shows a complex northerly migrating spit system with sand reworked from the earlier Holocene barrier
18. Cape Frezier area	outcrop of Mesozoic rocks, Tertiary ferruginous sandstone, and Pleistocene red dune sand; a complex of Mesozoic, Tertiary, Pleistocene, and Holocene Formations	reworking of Pleistocene red dune sand along coast to form Church Hill Sand, Barn Hill Formation, and coastally derived Shoonta Hill Sand
19. Anna Plains	stranded coastal plain underlain by Sandfire Calcilutite; located between hinterland of Mesozoic rocks and Pleistocene red dune sand	this area illustrates the inland extent of the post-glacial Holocene marine incursion into a deeply indented funnel-shaped embayment, and accumulation of Sandfire Calcilutite
20 Eighty Mile Beach (Mandora area)	seaward edge of the prograded coastal plain in the funnel-shaped embayment; Holocene units include Port Smith Sand, Sandfire Calcilutite, Shoonta Hill Sand, and locally, Eighty Mile Beach Coquina	barrier dunes, samphire-vegetated prograded mud flats, with lines of inland barriers and cheniers, representing the prograded coastal plain residing in the funnel-shaped embayment of the Salt Creek drainage line; the main progradation took place with sea level + 2 m above present and continued with sea level + 1.5 m above present, earlier stages of coastal retreat are marked by stranded inland sand barriers; currently, the coast is in a stage of retreat with development of a shore-linear barrier with stratigraphic development of a series of cut-and-fill structures; the periods of major coastal retreat are marked by the Eighty Mile Beach Coquina

21 Mandora Marsh area	samphire-vegetated flat on the margin of the funnel-shaped embayment of the Salt Creek drainage line; bordered by Pleistocene red dune sand underlain by the Sandfire Calcilutite	this area illustrates the extent that carbonate sedimentation had progressed in the funnel-shaped embayment by *circa* 5000 yrs BP, when MSL had fallen from its + 2 m maximum to a level 1.5 m above present; as an indurated unit, it also shows that the landward margin of the Sandfire Calcilutite in the zone of freshwater discharge from the red dune sand hinterland results in induration
22. Sandfire area	samphire-vegetated flats cradled between Pleistocene red dune sand (= Mowanjum Sand) underlain by the Sandfire Calcilutite	this area illustrates the inland extent of the post-glacial Holocene marine incursion into a deeply indented funnel-shaped embayment, with accumulation of Sandfire Calcilutite; radiocarbon date of *circa* 7500 yrs BP shows that carbonate mud sedimentation was dominant
23. Salt Creek area	samphire-vegetated flats cradled between Pleistocene red dune sand underlain by calcreted Pleistocene calcilutite	the largest mud-filled embayment in the region; this area shows the inland extent of the earlier pre-Holocene marine incursions into the Salt Creek valley tract, with accumulation of calcilutite
24. Wallal Downs area	prograded coastal plain in the southern part of the funnel-shaped embayment of the Salt Creek system; hinterland of Pleistocene red dune sand and Pleistocene oolite ridge; Holocene units include Horsewater Soak Calcarenite, Port Smith Sand, Sandfire Calcilutite, Shoonta Hill Sand, and Eighty Mile Beach Coquina; locally, Horsewater Soak Calcarenite is exposed at the coast and is cliffed	similar to the central Eighty Mile Beach area, this tract of coast illustrates the extent that carbonate sedimentation had progressed in the funnel-shaped embayment by *circa* 4300 yrs BP, when MSL began to fall from its + 2 m maximum to a level 1.5 m above present; currently, the coast is in a stage of retreat with development of a shore-linear barrier with development of a series of cut-and-fill structures, and bodies of Eighty Mile Beach Coquina
25. Shoonta Hills area	an earlier Holocene barrier/spit (underlain by Willie Creek Calcarenite, Kennedys Cottage Limestone, and Horsewater Soak Calcarenite) sheltering an embayment wherein the Sandfire Calcilutite accumulated; hinterland is Pleistocene red dune sand	the earlier Holocene barrier/spit emanating from the Pleistocene dune sand headland has upward shoaling stratigraphy (Willie Creek Calcarenite, Kennedys Cottage Limestone, and Horsewater Soak Calcarenite) formed with MSL + 2m above present; later Holocene units of Cable Beach Sand and Shoonta Hill Sand overlie (or are perched on) the Holocene calcarenites
26. Cape Keraudren area	a complex of barriers of Pleistocene limestones with intercalated palaeosols, Holocene calcarenites (Horsewater Soak Calcarenite overlying Kennedys Cottage Limestone, which rests unconformably on Pleistocene limestone) and modern dunes (Shoonta Hill Sand); the barriers shelter an embayment wherein accumulates(ed) the Sandfire Calcilutite	radiocarbon date from the lower part of Sandfire Calcilutite on the inland part of a prograded tidal flat shows the barrier was sheltering the mud-filling embayment by *circa* 7300 yrs BP; MSL indicators in the Holocene barrier and the elevated position of the Crab Creek Calcilutite Member (2.5 m below the present surface flat which itself is above HAT) indicate MSL was at least + 2 m above present level
27. Pardoo Creek area	series of Pleistocene oolite ridges with swales filled with the Crab Creek Calcilutite Member of the Sandfire Calcilutite	southernmost part of the Canning Coast wherein calcilutite accumulation was taking place within an ancestral framework of Pleistocene oolite ridges, with mud accumulating in the swales between the oolite ridges

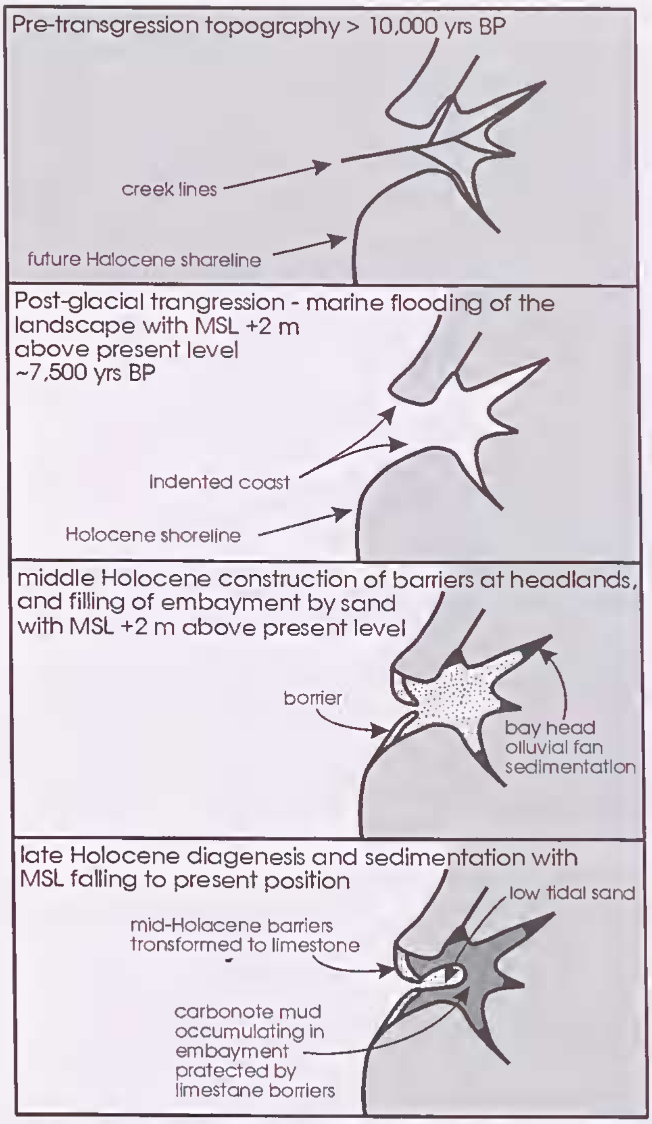


Figure 38. Evolution of coastal deposits in an indented embayment developed by the small pre-Holocene creeks in the area. These small embayments are typified by Willie Creek, Port Smith, Lagrange Bay, and Cowan Creek.

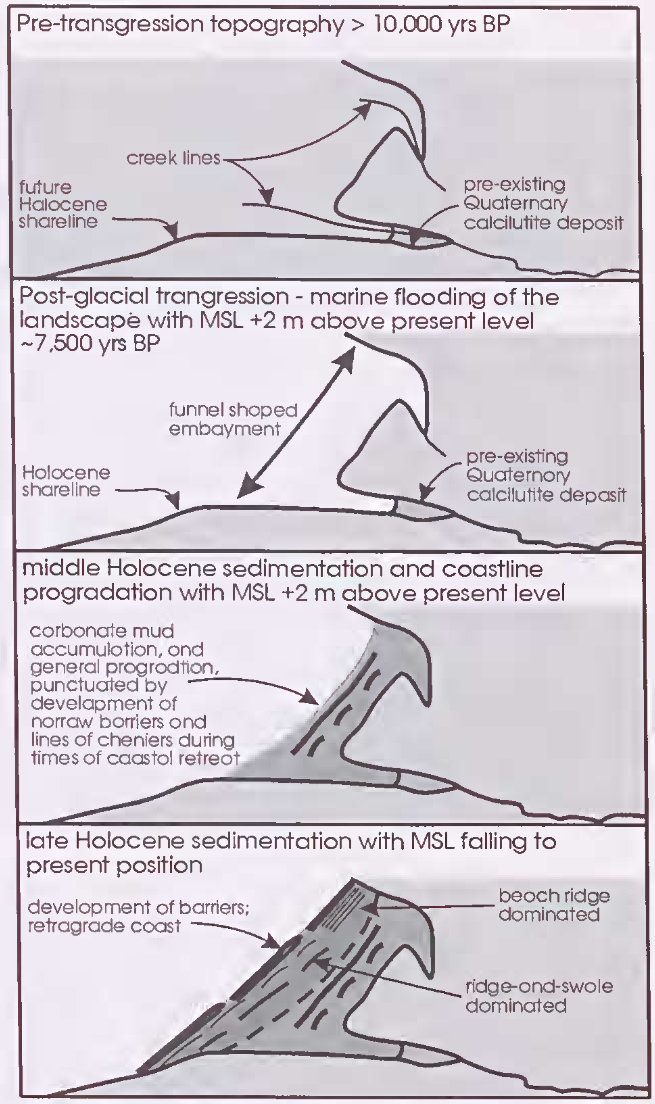
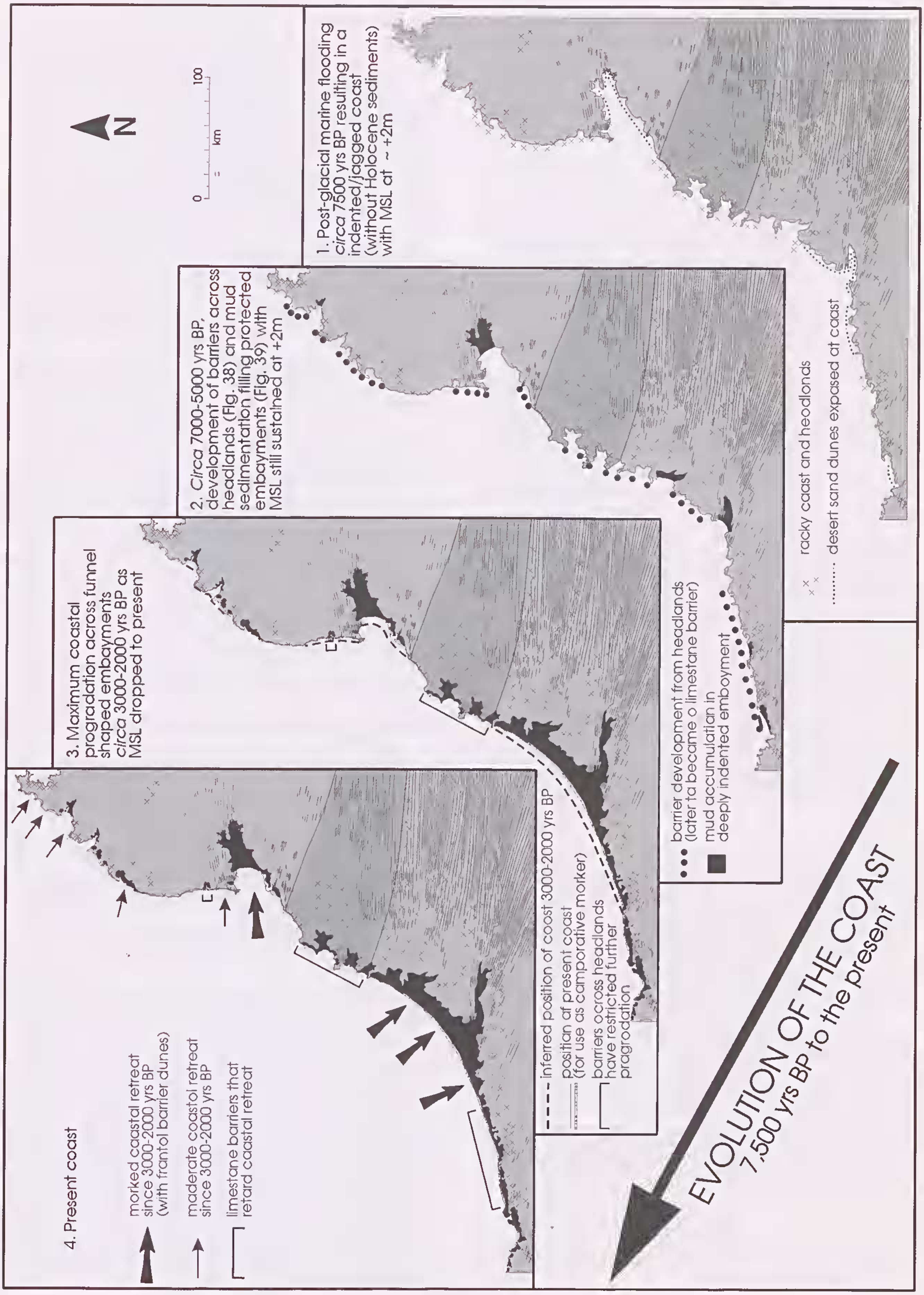


Figure 39. Evolution of coastal deposits in a large funnel-shaped embayment developed by the dominant pre-Holocene creeks and lowlands in the area as typified by the Samphire Marsh (Mandora Marsh) and Anna Plains area, and Roebuck Bay.

mud-dominated sedimentation and coastal progradation to an alternating progradation-and-retreat style of coastal development.

The occurrence of ooids along the length of the Canning Coast, and from earlier Holocene accumulations to the present suggests that there has been no significant change in oceanic hydrodynamics and seawater hydrochemistry along this coast over the period of the middle Holocene to the present. Similarly, the occurrence of beachrock and the derivatives of beachrock (*viz.*, conglomerates and boulder deposits) from earlier Holocene deposits to the present suggest that seawater hydrochemistry and the occurrence of cyclone events have more or less remained the same.

Figure 40. Simplified Holocene palaeogeography of the Canning Coast shown in four stages (in all stages the coast is drawn at MSL and does not depict its mid-tidal to low-tidal portions). The hinterland physiography of highlands, outcrops and linear dune fields is based on Figure 4. (1) the shape of the Canning Coast after initial flooding by the post glacial transgression *circa* 7500 yrs BP with the coast being highly irregular reflecting marine incursion firstly into major valley tracts with MSL *circa* 2 m higher than present (resulting in funnel shaped embayments), and secondly into smaller low relief dissected terrain (resulting in small scalloped embayments and their adjoining rocky headlands of Pleistocene limestone and/or Mesozoic rock). (2) the regional patterns developed with sea level *circa* 2 m above present (about 7000–3000 yrs BP), with sandy barriers emanating from the rocky headlands (later to be transformed to limestones) barring the embayments, and partial filling with mud of the deeply indented embayments. (3) the regional patterns developed with sea level dropping to about present level (about 3000–2000 yrs BP) – where it was possible and unimpeded by limestone barriers, the coasts have rapidly prograded, following the lowering of sea level, and extended seawards beyond their present positions; and have progradationally filled the larger funnel-shaped embayments; while this progradation buried many of the headlands, it did not fully subsume all rocky headlands. (4) the shape of the present coast with nearly completed filling of larger embayments, but with a general smoothing of the coast as a result of coastal retreat and barrier dune development and widespread coastal erosion particularly along the Eighty Mile Beach Sector (Tract 3). ▶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0 km 100
1. Post-glacial marine flooding circa 7500 yrs BP resulting in a indented/jagged coast (without Holocene sediments) with MSL at ~ +2m
rocky coast and headlands
desert sand dunes exposed at coast
2. Circa 7000-5000 yrs BP, development of barriers across headlands (Fig. 38) and mud sedimentation filling protected embayments (Fig. 39) with MSL still sustained at +2m
barrier development from headlands (later to became a limestone barrier)
mud accumulation in deeply indented embayment
3. Maximum coastal progradation across funnel shaped embayments circa 3000-2000 yrs BP as MSL dropped to present
inferred position of coast 3000-2000 yrs BP
position of present coast (for use as comparative marker)
barriers across headlands have restricted further progradation
4. Present coast
marked coastal retreat since 3000-2000 yrs BP (with frontal barrier dunes)
moderate coastal retreat since 3000-2000 yrs BP
limestone barriers that retard coastal retreat
EVOLUTION OF THE COAST
7,500 yrs BP to the present

However, there are indications that there have been changes in climate. The channelling of the Holocene sequence and its filling with Christine Point Clay between 2400 (-2600) yrs BP and 1800 yrs BP in the Camp Inlet area suggest a time of increased rainfall. Such increased rainfall would have resulted in increased release of terrigenous clays from the Pleistocene dunes of the Dampier Peninsula hinterland, and an increased delivery of this clay to creeks cut into the tidal flats. Concomitantly, with more humid conditions, soils were developed on a stabilised dune system (the Shoonta Hill Sand); a radiocarbon date of midden shells within these soils is 2440 yrs BP, an age more or less similar to the age of the channelling noted above.

Subaerial cementation of sand dunes in the Shoonta Hill Sand, Barn Hill Formation, or in the earlier Holocene Formations of Horsewater Soak Calcarenite and Kennedys Cottage Limestone to form calcarenites appears to be rapid in this region. This is interpreted partly to be related to the (metastable aragonitic) ooid content of the sands, and to the tropical climate. Similar rapid cementation of oolitic sands and in coquinas has been documented in modern aragonitic ooid sand dunes and aragonitic shell beds (the Hamelin Coquina) in the Shark Bay (Logan 1974), an area that is located in a subtropical arid climate.

Middens throughout this region provide an interesting scope for future work. The model of coastal sedimentation and its variable stratigraphic expression provides a framework to interpreting the location and compositional variety of middens in this region. A dynamic coast, temporally and spatially varying in the low-tidal zone from sand to muddy sand to mud, generating zones of coastal rock (calcarenites and beachrock), and changing in its mangrove characteristics would provide a rich resource for food, albeit dynamic in composition. The information on stratigraphy and temporal variation in coastal systems presented in this paper thus can provide a framework to interpreting the varying occurrence and diversity of middens in this region.

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